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GROUND SUPPORT PREDICTION MODEL (RSR CONCEPT)

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13. ABSTRACT

A methodology is described for predicting rock tunnel support requirements in the pre-construction period, based on geologic investigation, and construction factors such as size and shape of opening, direction of drive and method of excavation to be employed.

Development of this method, known as the Rock Structure Rating (RSR) concept, was begun under U.S. Bureau of Mines Contract No. H0210038 and completed under Contract No. H0220075. Work performed under the previous contract is reviewed. Based on a case history study approach, it utilized data from 33 tunnel projects to develop a tentative prediction model. The Rock Structure Rating is a measure of the ability of a rock mass to support itself around a given tunnel opening by assigning weighted ratings to important geologic and construction factors affecting this ability. This combined rating (RSR) is correlated to actual support systems, resulting in an empirical relationship which can be used to project support predictions for future tunnels.

Development of a modified and expanded prediction model is described based on additional research. Twenty case studies were added bringing the total to 53. Seven mining operations were investigated to check the applicability of the prediction method to mining. Twenty-five prominent men and agencies involved in tunneling reviewed the method, completed questionnaires and offered comments and suggestions.

The resulting revised prediction model was used to predict support requirements for six on-going tunnel projects and verification of actual supports used, made by field site visits where possible. Results of these field investigations are given and analyzed.

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Geologic Predictions						
Support Requirement Charts						

GROUND SUPPORT PREDICTION MODEL

(RSR CONCEPT)

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PREFACE

This report sets forth final results of continued research in the development of a Ground Support Prediction Model (RSR Concept) for practical usage to civil and/or mining applications. The study effort was undertaken by Jacobs Associates in accordance with terms of Contract No. H0220075 dated June 7, 1972 with the Bureau of Mines, Department of the Interior. It is an extension of work previously performed under Contract No. H0210038 and is part of ARPA's Military Geophysics program directed toward improvement of underground rapid excavation technology.

The Contracting Officer is Mr. Frank Paviich, Bureau of Mines, Denver Federal Center; the Project Technical Officer is Mr. Eugene H. Skinner, Spokane Mining Research Laboratory. Mr. Skinner has taken an active part in the research effort being part of the field study team, and has contributed information contained in Appendexes D. & E. Historical tunnel data and records used in developing the prediction model were provided by different government and private agencies. Many individuals of the construction industry provided suggestions, comments and criticisms of the RSR concept which were most helpful in final evaluations. Both civil and mining operators were very cooperative during the inspection and gathering of field data pertaining to on-going projects. The help and assistance of these and others who contributed to the research effort is fully appreciated.

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INTRODUCTION

The need for ground support research in rapid underground excavation has been well identified in recent years. Two of the major problem areas are: 1) to find means of predicting rock loads in advance of actual construction; and 2) to develop methodology for determining safe, efficient, and economical ground support design practices.

Noting these needs, the Bureau of Mines, acting as agent for the Advanced Research Projects Agency, has undertaken contract research efforts relating to the problem. One such study - "Research in Ground Support and Its Evaluation for Coordination with System Analysis in Rapid Excavation" (1)* developed and proposes a methodology for predicting subsurface conditions based on pre-construction geologic data and correlating such predictions with appropriate ground support systems. The overall methodology developed is the Rock Structure Rating (RSR) concept. The purpose of the present research is to extend this prior work to areas of limited data; to evaluate industry acceptance of the RSR techniques, to undertake field implementation and to assemble findings and data into final format emphasizing its usage. In addition, the appendixes of the report contain brief comments and review of new concepts of ground support, rock and support classification methods and remote sensing devices all of which are relevant to the general area of predicting ground support for future tunnels.

* refers to reference at end of report.

SUMMARY

The difference between a successful and unsuccessful tunneling operation can usually be traced to some form of 'misinterpretation" of sub-surface conditions during the pre-construction period. Although present tunnel site investigations normally provide adequate localized geological information, in many instances projections to tunnel grade and the resulting influence on support requirements, are dependent on the individual making the projection. This is due partly to differences in discipline oriented methods of evaluating and analyzing available data; lack of an accepted common method of correlating past tunneling experiences with conditions of on-going or future projects and lastly, the ever present legal conflict of responsibility when encountered sub-surface conditions are not the same as anticipated.

A technique or procedure which would provide a reliable method of predicting and projecting support needs for the rock structure to be penetrated would be of great benefit to the tunneling industry. Barring the unlikely event of an early breakthrough in geophysical techniques; any improvement of the 'art' of predicting sub-surface conditions must rely heavily on better utilization and correlation of past tunneling experiences with data and information available from present technologies of tunneling, geology, and rock mechanics.

The ground support prediction model described in this report presents a solution to this problem. It is based on an empirical relationship between

actual ground support installations and prebid geological information as determined from a study and review of 53 tunnel projects. The model considers and incorporates the experience, judgment, and opinions of qualified individuals involved in all aspects of underground construction. The format of the RSR model is presented in terms commonly used in the tunneling industry, is fairly simple to use, and is capable of "up-dating" or modification as may be dictated by continued use or inclusion of more exacting data which might become available.

In essence the RSR method provides a common method for evaluating and rating, on a numerical scale, the competency or physical quality of a rock structure with respect to its need for structural support. This is accomplished by use of three weighted parameters, each of which considers the relative effect on the support requirement as occasioned by various combinations of geologic and construction factors. Quantitative and qualitative appraisals of several factors; such as rock type, strike and dip, joint pattern and direction of drive can normally be made on the basis of information available in the pre-construction period. The weighted value assigned to each parameter is determined by considering the appropriate limits of measure and possible occurence of respective factors as depicted on the model format. A Rock Structure Rating (RSR) is obtained as the sum of values determined for each of the three parameters. It is a relative measure of the rock structures need for support irrespective of tunnel size, and provides a means of correlating geological information with actual or predicted support requirements.

Empirical relationships between determined RSR values, rock loads,

tunnel size and steel rib, rock bolt, and shotcrete support were developed from case history data and various theoretical and analytical methods of ground support determination. Support requirement charts are presented herein which delineate appropriate support systems required for various sized tunnels driven through different ranges (different RSR values) in rock structures. They do not include or apply to soft ground or squeezing ground conditions.

The overall concept of the ground support prediction model was critically reviewed by 25 individuals of the tunnel industry. Suggestions, criticisms, comments, changes and modifications have been incorporated in the RSR as deemed appropriate. The general consensus was 1) a ground support prediction model is needed, 2) empirical correlation of geology and ground support is a reasonable approach, 3) the proposed model considers and evaluates the most important factors involved in determination of ground support, 4) the model should be expanded to include a greater variety of tunneling situations, 5) dimensional rather than descriptive terminology should be used to define geologic factors, and 6) provides a common means of comparing, checking and correlating encountered conditions with predictions and/or results obtained by use of other techniques.

It would be impossible to consider and treat separately all situations and respective requirements as expressed by various disciplines involved in tunnel construction. Consequently the prediction model is structured so as to present a reasonable compromise between theory, actual practice and other presently accepted standards or criterion. It is not intended to be an exact measure of a particular support member at a specific location but rather to make

realistic appraisals of overall support requirements for future tunnels.

The validity or reliability of the model was, and is being, tested by field application to several on-going projects. Results to date, although not conclusive, show a reasonable correlation between predicted support requirements and actual installations. Practical usage to either mining or civil applications depends to a large extent on the degree of confidence developed through continued use.

The attached appendixes include: A - Individual comments pertaining to the RSR evaluation. B - Descriptions and evaluation of newly developed tunnel support methods and innovative support methods proposed in connection with these contracts. C - An example of RSR concept application to a hypothetical tunnel situation. D - A discussion of rock classification systems. E - A discussion of remote sensing systems as applied to geologic investigations.

ARPA RECOMMENDATIONS

Achieving the defined goals of ARPA related to underground rapid excavation required the development of (1) a more reliable method of predicting ground support requirements, and (2) an adequate ground support system which can be installed with little or no reduction in the anticipated heading advance rates of unsupported tunnels. The Rock Structure Rating (RSR) and the Rib Ratio (RR) procedures, and the ground support concepts developed in this contract provide means for achieving the goals of safe, efficient, and economical ground support systems suitable for the needs of the Department of Defense (DoD) military oriented programs as well as having civil and mining application.

SECTION 1

ROCK STRUCTURE RATING CONCEPT

1.1 INTRODUCTION

An objective of the present research effort was to extend, verify, and modify the ground support prediction model previously developed under Contract No. H0 210038 (1). This section of the report presents a general review of the methodology used in developing the initial model which is referred to as the Rock Structure Rating (RSR) concept. Appropriate revisions and modifications determined from the present research effort are discussed in Sections 2, 3 and 4. The finalized prediction model including appropriate derivations is presented in Section 5.

1.2 BACKGROUND

In most cases the inclusion of the ground support subsystem in the overall tunneling process has a very adverse effect on daily advance rates that could otherwise be achieved in driving an unsupported tunnel. This is especially true when using a boring machine or other innovative method of excavation. Delays are due largely to the inability of knowing in advance the need for or type of ground support which may be required.

Advancing a heading at 200 feet or more per day, allows little time for making ground support determinations on the basis of in situ test data. The use of long horizontal probe holes ahead of the face give indications of potential major problems more than suggesting support requirements. These

and other limitations of present techniques point out the necessity for developing some method by which an adequate support system and associated method of installation can be determined in the pre-construction period and realistically projected along the tunnel line. Within limits of present-day technology, these determinations must be based on predictions of subsurface conditions and subsequent evaluation of the relative effect of all pertinent geologic and construction factors on the ground support requirement.

Any prediction method is essentially an 'art' which in the case of ground support, involves the collective consideration of personal experiences, judgements and observations as well as results, findings, and conclusions derived from the sciences of geology and rock mechanics. Present improvement of the 'art' depends to a large extent on better utilization and correlation of historical tunneling data with theoretical design and practical experience of many years of tunnel construction. This process is complicated by: 1) discrepencies in terminology and respective meaning as used by different disciplines to describe or define pertinent factors and their resulting effect on support requirements; and 2) the fact that no two tunneling situations are identical with respect to either geological conditions or construction and contractual requirements.

Any attempt to critically analyze and evaluate all possible combinations of factors inherent to the prediction of ground support would be virtually impossible and would not be warranted when viewed with respect to the overall tunneling operation. However, it is desirable that some form of a

prediction method be developed which would provide realistic solutions to be used in the planning and construction of future tunnels; be capable of common evaluation by various disciplines and alleviate as much as possible the perpetual controversies arising from 'changed conditions'.

There has probably been numerous occasions where similar solutions have been reached, even though there may have been significant differences in methods of analysis and approach to the problem. Seldom, however, are such determinations, reasoning or conclusions adaptable to comparison or evaluation with respect to each other or to future projects. In many instances it would be difficult to subsequently re-evaluate a specific project for reasons why the initial support prediction had or had not been correct.

The RSR prediction model provides a standard approach with the potential for uniform solution to the problem. It is not intended to technically define a particular structural support member for a specific tunnel location, but rather to make an evaluation of a support system which would afford a near optimum solution to the tunneling process. It is an effort to bridge the gap between a highly theoretical analysis and the more practical aspects of the tunnel constructors. Although no prediction model could be all inclusive for every possible situation, the RSR concept gives a fairly straightforward common basis for evaluation and correlating major geologic and construction factors which affect support requirements for most rock tunnels. In a general way, it could be compared to procedures used to define or rate many other engineering materials, such as timber, wherein each board is graded with

respect to numerical occurrence and limits of measure (size of knots, etc.) of various defects which are present. The RSR method is essentially an empirical approach to the problem, based on historical data; review and evaluation of findings and conclusions presented in published papers pertaining to geology, rock mechanics and theories of support determinations, and consideration of the practical aspects of tunnel construction. It can be modified as may be dictated by field testing, continued research or critical review by the tunnel construction industry. The reader is referred to References 1 and 2 for additional detail regarding the RSR concept.

1.3 FACTORS AFFECTING GROUND SUPPORT

The need for ground support depends on the physical competency of the rock structure or its ability to support itself when penetrated by the tunneling operation. Approximation of this need can be made by considering various geologic and construction factors which in one way or other affect the quality or condition of the exposed structure. The RSR concept groups pertinent factors into three basic parameters, each of which is subsequently evaluated with respect to their individual or combined relative effect on the support requirement. Geologic factors include: 1) rock types, 2) joint patterns, 3) dip and strike, 4) discontinuities, 5) faults, shears and folds, 6) ground water, 7) rock material properties and 8) weathering or alteration. Construction factors relate to: 1) size of openings, 2) direction of drive and 3) method of excavation.

Although it is apparent that comments could be made as to whether or not the above factors are all inclusive; reflect most important considerations; or are synonymous or ambiguous in meaning, they do relate to those conditions commonly considered in determining support requirements and are usually definable to some degree from information provided in the preconstruction period.

Geologic factors can be considered individually within a range of possible occurrence and collectively with respect to their relative effect on the rock structure. For instance, a rock may be described in terms of hardness; such as Mohs' scale or other analogies, and also in terms of various joint or fracture patterns. An overall evaluation must consider both properties or conditions and the relative mix of each. It is also necessary to consider the various geologic factors with respect to size of opening, direction of drive and method of excavation. Each combination of geologic and construction factors requires that different evaluations be made in determining the need for ground support. An appraisal of the above factors with respect to the RSR concept is given in Reference 1.

1.4 DEVELOPING THE RSR CONCEPT

One or more predictions of ground support requirements are made for every tunnel that is constructed. They are usually based on an individual's personal evaluation of available geologic and construction data which would affect the tunneling process and generally include information obtained from site and core inspections, review of geology reports and past tunneling

experience. Although considered factors and analyses may differ, most individuals probably use similar methods of evaluation. The RSR concept attempts to put this general thought process for evaluating rock structure into a format which could be commonly used and understood by all involved in tunnel construction. It was apparent that all requirements expressed by different disciplines could not be treated separately, consequently, various generalizations and compromises were made, all in keeping with the goal of reaching realistic solutions. Consideration was made of the following:

1) Typical geologic information available in the pre-construction period.
2) Types of geological investigations used and reliability of developed data.
3) Most important geologic factors to be considered with respect to their effect on the physical condition of the rock structure.
4) Methods of measuring the qualitative and quantitative properties of each factor.
5) Relative effect on ground support requirements.
6) Development of a general method or procedure of rating the rock structure.

Since the direction of drive with respect to the strike and dip of the formation affects the apparent quality of the rock structure, this factor is also included in the RSR concept. The physical effect on support requirements due to size of opening and method of excavation are treated separately.

A basic format was established which listed all factors and limits of measure for both quantitative and qualitative properties. A weighted numerical value was assigned, which reflected the relative effect of the factor on the overall support requirement, the rock structure rating being the sum of weighted values determined for the applicable factors. The higher numbers indicating 'good' ground conditions, wherein little or no support would be required, the lower numbers indicating various degrees of heavier support. The initially assigned weighted values were based on evaluations of actual tunneling situations similar to those envisioned for the prediction model. Although there was a tendency to include all factors and combinations thereof, it was realized that the detailed information needed for such an approach would rarely be available in the pre-construction period. Also, inherent unknowns in any prediction of subsurface conditions are such that attempts to specifically define all factors would not be warranted. Consequently, the original concepts were revised and condensed into three basic parameters as shown on Figure 1.1. The parameters include most of the above mentioned factors and indicate the combined relative effect on ground support requirements as determined for various combinations and conditions. They also reflect the interdependency of different factors in the overall evaluation of the rock structure.

Parameter A is a general appraisal of rock structure through which the tunnel is to be driven. Geological information needed to define the limits of measure and describe the stiucture is available in the pre-construc-

ROCK STRUCTURE RATING
PARAMETER "A"
GENERAL AREA GEOLOGY

BASIC ROCK TYPE	GEOLOGICAL STRUCTURE			
	MASSIVE	SLIGHTLY FAULTED OR FOLDED	MODERATELY FAULTED OR FOLDED	INTENSELY FAULTED OR FOLDED
IGNEOUS	30	26	15	10
SEDIMENTARY	24	20	12	8
METAMORPHIC	27	22	14	8

ROCK STRUCTURE RATING
PARAMETER "B"
JOINT PATTERN
DIRECTION OF DRIVE

AVERAGE JOINT SPACING FEET	STRIKE ⊥ TO AXIS					STRIKE ∥ TO AXIS		
	DIRECTION OF DRIVE					DIRECTION OF DRIVE		
	BOTH	WITH DIP		AGAINST DIP		BOTH		
	DIP OF PROMINENT JOINTS					DIP OF PROMINENT JOINTS		
	FLAT	DIPPING	VERTICAL	DIPPING	VERTICAL	FLAT	DIPPING	VERTICAL
< .5 (CLOSELY JOINTED)	14	17	10	16	16	14	15	12
.5-1.0 (MODERATELY JOINTED)	24	26	30	20	24	24	14	20
1.0-1.0 (MODERATE TO BLOCKY)	32	34	38	27	30	32	30	25
2.0-4.0 (BLOCKY TO MASSIVE)	40	42	44	36	38	40	37	30
> 4.0 (MASSIVE)	45	46	20	42	45	45	42	36

Flat 0 - 20°
Dipping 20° - 20°
Vertical 20° - 90°

ROCK STRUCTURE RATING
PARAMETER "C"
GROUND WATER
JOINT CONDITION

ANTICIPATED WATER INFLOW (gpm/100u')	SUM OF PARAMETERS A + B					
	20-45			46-80		
	JOINT CONDITION					
	1	2	3	1	2	3
NONE	10	12	10	20	18	14
SLIGHT (<200 gpm)	17	12	7	18	15	10
MODERATE (200-1000 gpm)	12	9	6	18	12	8
HEAVY (>1000 gpm)	8	6	5	14	10	6

Joint Condition:
1 - Tight or Cemented
2 - Slightly Weathered
3 - Severely Weathered or Open

Figure 1.1

tion period. It is usually presented in terms compatible to all disciplines, such as "massive granite" or "intensely folded serpentine". The assigned weighted value for Parameter A in the first instance would be 30; in the second, 9.

Parameter B relates the joint pattern (strike, dip and joint spacing) and the direction of drive. Most surface geology surveys or maps give an indication of the strike and dip of various formations. Therefore, such data is ordinarily available. Direction of drive is determined from project planning. There are usually several sources of information that can be used in determining the anticipated average joint spacing of the rock structure. Geological terms such as "closely jointed" or "blocky", driller's logs, core analysis or RQD indices are examples. Geology reports usually give some description of anticipated joint spacing. Defining this factor is difficult but it is felt that reasonable approximations can be made by considering all available information. For purposes of the RSR method of evaluation, five numerical limits of measure were chosen for joint spacing. The respective bracketed words in the left hand column of Parameter B (Figure 1.1) are used to show intended correlation or equivalency between the given numerical limits and common geological terminology. The value to be assigned to Parameter B can be obtained from the table by considering appropriate limits of measure determined for joint spacing with respect to applicable strike and dip of the formation and direction of drive.

Parameter C takes into consideration the following: 1) the overall quality of the rock structure as indicated by the numerical sum of values assigned to Parameters A and B; 2) the condition of joint surfaces, and 3) the anticipated amount of water inflow. Establishing limits of measure or estimating possible occurrence of the last two factors is normally left to the discretion of the contractor. Data pertaining to pump tests, local wells, ground water levels, surface hydrology, topography and rainfall should be considered in conjunction with the anticipated geological formation in estimating ground water inflows. Condition of joint surfaces would be appraised from surface or historical geology, driller's log or inspection of core samples. The RSR method allows for three types or conditions of joint surfaces which are described as: 1) tight or cemented, 2) slightly weathered and 3) severely weathered or opened; and four quantitative estimates of water inflow. The value assigned to Parameter C is obtained from the table by using the limits of measure determined for the different factors.

The RSR value of the particular geological section under consideration is the numerical sum of Parameters A, B and C. These values, which range from 25 to 100, reflect the quality or competency of the rock structure regardless of size of tunnel opening or method of excavation. Each distinct formation penetrated by the tunnel would require separate analysis with respect to RSR values.

To verify the appropriateness of the concept, a study was made of previous tunnel construction records to see if reasonable evaluation of the

quality of the rock structure could be made. Some 33 tunnels were studied, each being divided, as appropriate, into separate geologic sections. This provided approximately 100 sample sections. In most cases, RSR evaluations were made on the basis of information which had been provided in the pre-construction period, in others, additional as-built data was used. Results indicated that in general, it would be possible to make a resonable apprais-al of the quality of the rock structure by use of the RSR concept in conjunc-tion with information normally provided in the pre-bid period. The next step was to develop some relation between the RSR values and support require-ments.

In order to make this RSR-support correlation it was necessary to develop a standard datum by which different supports could be compared on a common basis. Since the majority of case history tunnels were supported with steel ribs it was decided to use a measure that would relate actual support installation to some theoretical support (rib size and spacing) which could be similarly determined for each study tunnel. This measure, desig-nated as the Rib Ratio (RR), was developed from Terzaghi's formula for deter-mining roof loads in loose sand below the water table (datum condition). See paragraph 5.3 for derivation of rib ratio concept. Using tables provided in "Rock Tunneling with Steel Supports"(3), the theoretical support spacing required for the same size rib as used in a given study tunnel section was determined for the datum condition. Rib Ratio is then obtained by dividing this theoretical spacing by the actual spacing and multiplying the answer by

100. For instance, if the theoretical spacing of a 6 WF 25 rib was determined to be 2 feet, for the datum condition, and the actual spacing of the same rib used in the study sample was 5 feet, the RR would then be 40. Or expressed otherwise, the sample tunnel used only 40% of the support required for the datum condition. Rib ratios for tunnels with widely spaced support would be low, and zero where no support was used.

It is apparent that different size tunnels, although having the same calculated RR, would require different weight or size of ribs for equivalent support. The rib ratio can be used as a common basis for correlating RSR determinations with actual or required support installations.

Charts were prepared which showed the relation between determined RSR values and corresponding rib ratios. RSR values were plotted on the vertical axis, respective rib ratios on the horizontal. Each chart was evaluated by determining the number of sample points falling within or near an envelope of curves developed for the average graph of all plotted points. Since rib ratios remain constant, it was possible to see what effect variations in weighted values assigned to different geologic factors or parameters used in RSR evaluations would have on the developed curve. Figure 1.2 shows the resultant graph plotted with respect to RSR and RR values determined for approximately 80 sample tunnel sections. The relatively narrow width of the band of these sample points, comprising the 90% envelope, indicates a reasonable degree of correlation. Assuming that the RSR evaluation did in fact reflect actual quality of the rock structure, it can be conclud-

ed that points falling above the average curve represent tunnels which were "over-supported" and those below, the curve; those tunnels in which marginal support was used. Most exceptions to the plotted envelope were shown to be in the "over-supported" category.

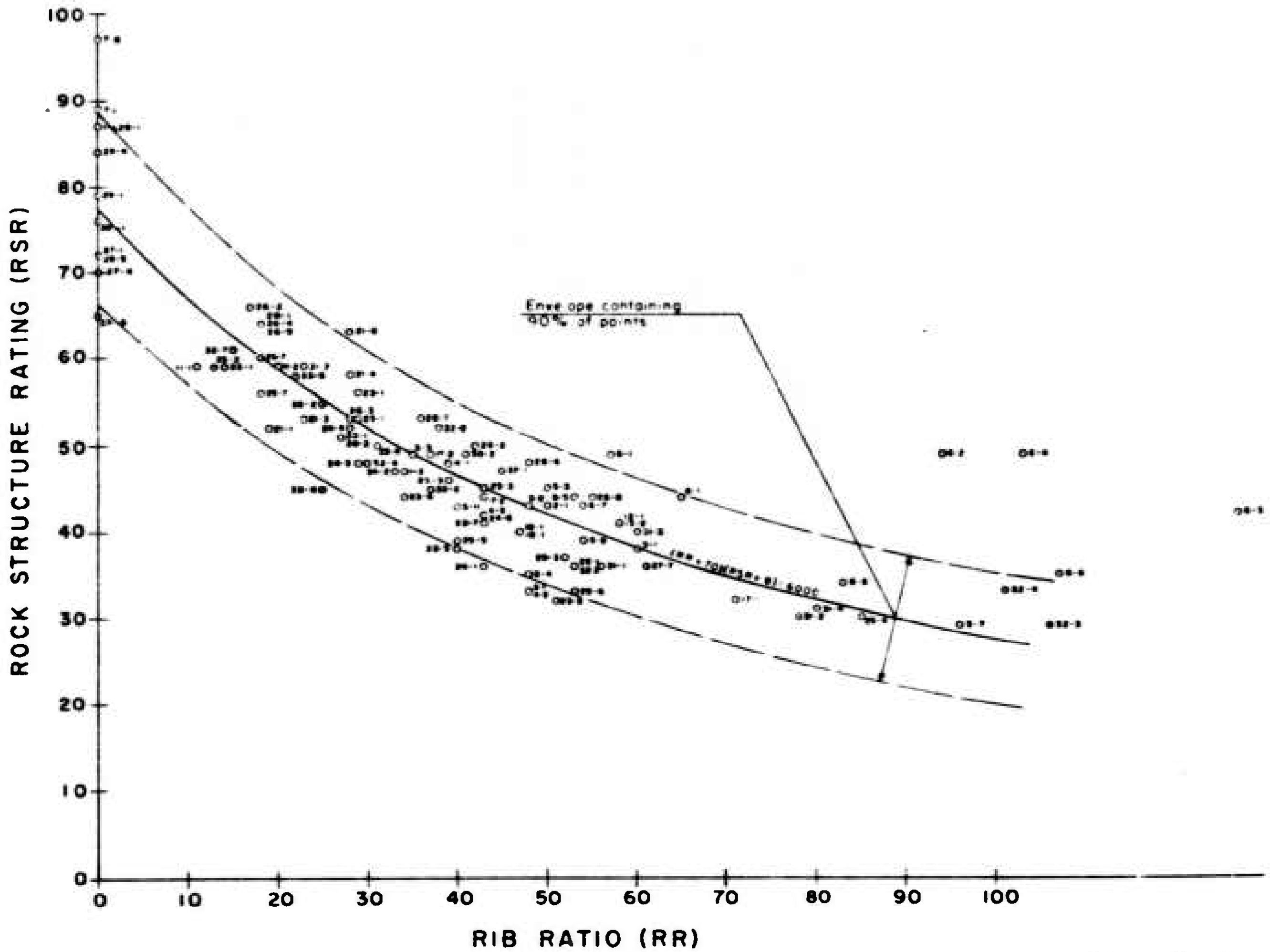
Using the equation for the average curve shown on Figure 1.2 it is possible to determine numerical rib ratios corresponding to different RSR values. Some typical relations at various RSR values are show below:

RSR Values and Rib Ratios
(Based on average curve equation - Figure 1.2)
$(RR + 70)\ (RSR + 8) = 6000$

RSR	27	30	35	40	45	50	55	60	65	70	77
RR	100	88	70	55	43	33	25	18	12	7	0

Rock structures with RSR values less than 27 would require heavy support; those with ratings over 77 would probably be unsupported. Structures with ratings between 27 and 77 would require varying amounts of ground support.

The rib ratio basically defines an anticipated rock load by considering the vertical load carrying capacity of different sizes of steel ribs, consequently the RSR values can be expressed in terms of unit rock loads for various sized tunnels. Derivation of this empirical relationship is given in paragraph 5.5. Typical results are shown below:



Original Correlation of RSR and RR*

Figure 1.2

*For latest correlation of RSR and RR see Section 5, Figure 5.4

Correlation of RSR with Rock Load
and Tunnel Diameter

Tunnel Diameter D (Ft)	Rock Load in Kips per sq. ft. (Wr.) 1.0	1.5	2.0	4.0	6.0	8.0
	RSR VALUES					
12	55.0	47.7	41.9	27.2	–	–
16	59.5	53.0	47.7	33.2	24.7	–
20	62.5	56.8	51.9	38.0	29.4	–
24	64.7	59.5	55.0	41.9	33.2	27.2
28	66.3	61.6	57.0	45.0	36.5	30.4
30	66.9	62.5	58.6	46.4	38.0	31.9

1.5 DETERMINATION OF SUPPORT REQUIREMENT

Requirements for a particular steel rib are usually expressed by the rib spacing determined for different rock loads and size of tunnels. The theoretical rib spacing determined for the datum condition reflects a rib ratio of 100 and corresponding RSR value of 27. Rib spacings for other RSR values (or equivalent rock loads) vary proportionately from the datum spacing as the inverse ratio of the respective rib ratios. The following example shows typical rib sizes and required spacing with respect to various RSR values and tunnel diameters of 16 and 20 feet.

Rib Spacing (ft) Based on RSR Values
and Tunnel Diameter

RSR Value	Tunnel Diameter: 16 Feet			20 Feet		
	Steel Rib Spacing					
	6H15.5	6H25	8WF31	6H 20	8WF 31	8WF 48
27	1.4	2.2	3.2	1.2	2.1	3.3
30	1.6	2.6	3.7	1.4	2.4	3.8
35	2.0	3.2	4.6	1.7	3.1	4.8
40	2.6	4.1	5.9	2.2	3.9	6.1
45	3.3	5.2	7.5	2.8	5.0	7.8

RSR	6H15.5	6H25	8WF31	6H 20	8WF 31	8WF 48
50	4.3	6.8	—	3.6	6.5	—
55	5.7	—	—	4.8	—	—
60	7.9	—	—	6.7	—	—

Historical data were found not sufficient to make reasonable correlation between rock structure and the use of rock bolt or shotcrete type of support. However, an appraisal of rock bolt requirements (spacing or pattern) can be made by considering rock loads with respect to the tensile strength of the bolt. This is a very general approach; it assumes adequate anchorage and that all bolts act in pure tension, only. It does not allow for interaction between adjacent blocks nor assumption of compression arch formed by the bolts. These and other conditions would probably be evaluated in detail design, but for purposes of the RSR evaluation the following relation is used for one inch rock bolts with a working stress of 24,000 psi.

Spacing or pattern of bolts (in feet) $= \sqrt{\frac{24}{Wr}}$

Where Wr = rock load in kips per sq. ft.

Although shotcrete support has been successfully used under many varied conditions, there is still no accepted theory to date as to its ultimate effect as a structural member. Most applications have been made on basis of rules-of-thumb. Various studies such as Sutcliffe and McClure (4) and Lauffer (5) have indicated a general relationship between thickness of shotcrete lining and other equivalent support systems. An attempt was made to correlate available theoretical and empirical data with some standard measure of the shotcrete requirement that could be related to geologic predictions.

Results were negative. Consequently the following empirical relationship is suggested. It is used in subsequent evaluations of shotcrete requirements:

$$t = 1 + \frac{Wr}{1.25}$$

Where t equals nominal thickness of shotcrete lining in inches and Wr = anticipated rock load in kips per sq. ft.

The preceding paragraphs have discussed various support requirements and have indicated common measures by which these requirements can be correlated with respect to geologic predictions and tunnel size. Using this data, it is possible to develop "Support Requirement Charts" for tunnels driven through different rock structures. A typical chart is shown as Figure 1.3. Other charts could be developed for different sized tunnels. The three steel rib support curves shown on the chart reflect typical sizes used for the particular tunnel diameter. Dashed portion of the respective curves indicate conditions for which the indicated rib size would probably not be used due to practical considerations. Curves for shotcrete and rockbolt requirements are similarly shown.

As indicated on the chart, there are usually several support systems which would satisfy the support requirement for most rock tunnels. The most appropriate or economical system to use would be determined from a cost analysis, taking into account the relative effect of each system on the overall tunneling process.

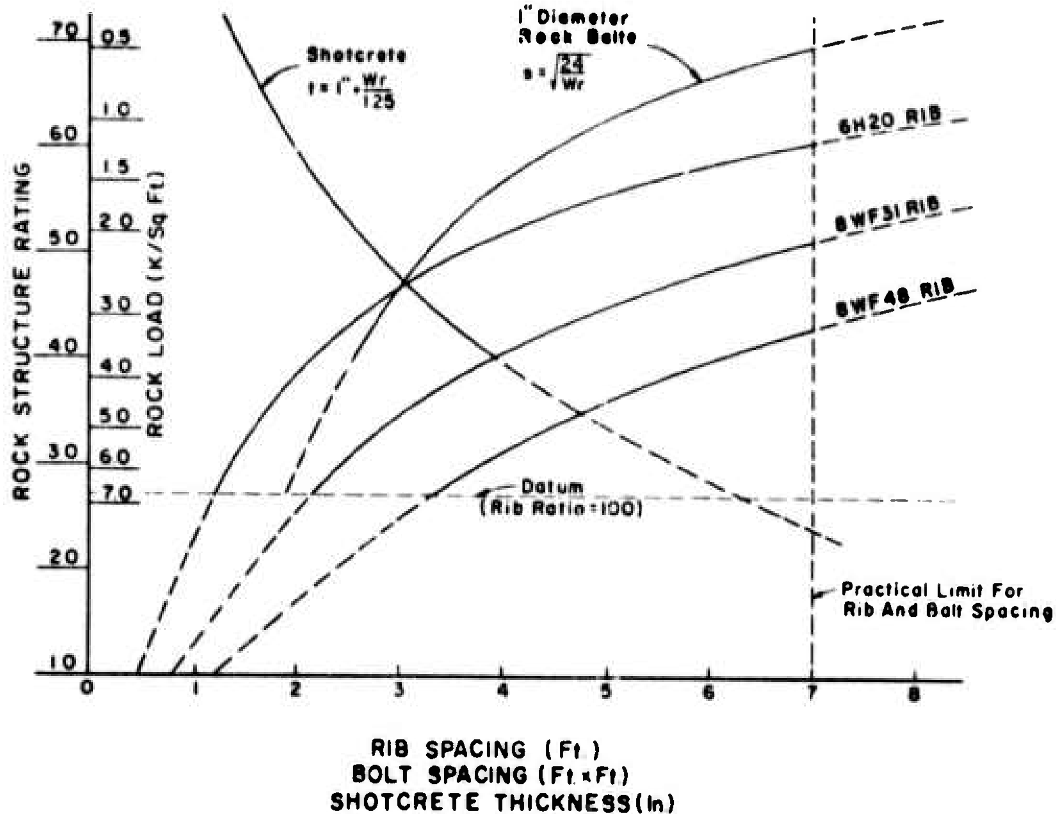


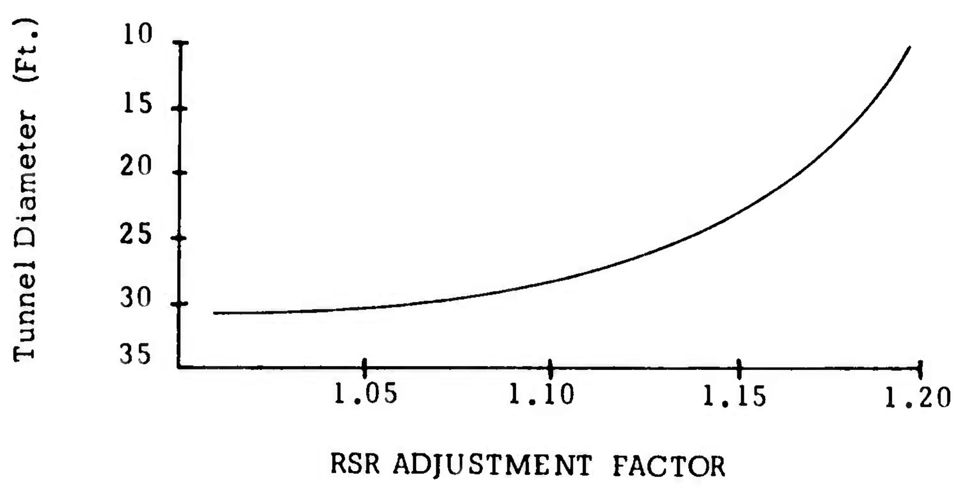
Figure 1.3 - Support Requirement Chart - 20' Diameter Tunnel

1.6 SUMMARY

The prediction of ground support requirement is based on case history data, the RSR method of evaluating rock structures, and the rib ratio measure. The datum condition used in developing the rib ratio is not critical, and could be changed without affecting the results. Although existing methods or theories of determining support requirements were considered, no comparative analysis was made between these and the proposed method. However, this could be accomplished by using the intrinsic relationship between rib ratios and rock loads. Most present support calculations consider loads in terms of feet of rock to be supported. Height (in feet) of the unit rock

column is defined as (n (B + H)) where n is a variable factor and B and H represent physical dimensions of the tunnel opening. Assuming the unit weight of rock as 165 lb. per cu. ft. and that B = H = D (for a circular tunnel) the factor "n" can be approximated by dividing rib ratios used in this study by 100.

The support requirement chart (Figure 1.3) reflects drill and blast tunneling operations. Although boring machines were used on several case study projects, information was not sufficient to make a reasonable correlation of support requirements between the two methods. Considering data that was available, it is suggested that the following procedure be used to determine support requirements for machine driven tunnels. The RSR value would be adjusted upward to reflect a better condition of the penetrated rock structure normally associated with the use of a boring machine. Such a factor might be defined as shown below:



RSR Adjustment for TBM Operation

For example - an RSR value of 50 has been determined for a 25 ft. tunnel. In considering appropriate support systems for a boring machine operation an RSR value of 58, (50 x 1.15) - would be used when entering the Support Requirement Chart.

Subsequent sections of this report discuss additional research undertaken to expand, modify or verify the original RSR ground support prediction model as outlined in this section. The same general procedures and methods as discussed here are used in both instances.

SECTION 2

CASE HISTORY STUDIES

CIVIL TUNNELS

2.1 INTRODUCTION

The basic data input used in the development of the Rock Structure Rating (RSR) concept was obtained by case history studies of previously constructed tunnel projects. The information sought in these studies consisted of three general categories: 1) physical dimensions and construction factors, 2) geology - prebid or as-built as appropriate and 3) actual ground supports placed during construction. The degree to which these data had been measured and recorded determined the reliability of the input. Where one or more categories were missing the project could not be effectively used in the study.

It was found that in general the quantitative data and quality of construction records is improving, especially since 1960. The well documented tunnel project of 1950 was an exception; today, fortunately it is not. In addition to pre-construction geological investigations, many agencies today use geologists to record actual ground conditions during tunnel driving. This latter information is usually given on as-built drawings together with construction data such as direction of drive, method of excavation, progress achieved, ground water flows encountered and the type, location, and amount of support. This amount of documentation is not only useful determining cost of construction and validity of possible claims; it also forms a valuable

guide for possible future construction planning. In addition to obtaining such data as described, there is a trend toward instrumentation to measure physical characteristics of the rock mass and its interrelationship with the tunnel opening.

While this presents an optimistic picture for future fact gathering, current studies must be based on the existing, less complete records of the past. The format for recording data for this study evolved with the development of the prediction concept, and is shown in final form as Figure 2.1. It allows for general tunnel data and detailed information needed for RSR computation for individual tunnel sections.

2.2 SCOPE

The initial RSR concept was based on data obtained from study of 33 construction projects. Although fewer projects had been originally contemplated, it soon became apparent that the number of variables affecting ground support requirements and the difficulty of assigning definitive values to many of them necessitated a great variety of situations to be examined. All tunnels whose records were made available were used if there was sufficient information to determine RSR values, and records of actual ground support were given. The majority of these tunnels were driven by the drill and blast method of excavation and used steel ribs as the primary means of ground support.

In order to refine and further develop the concept, it was decided that additional case studies in the second year be made primarily with re-

CASE HISTORY NO:________ NAME OF TNL:________ OWNER:________

LOCATION:________ APPROX. ELEV:________ DATE OF CONST:________

EXCAV. SIZE:________ TOTAL LENGTH:________ EXCAV. METHOD:________

PRE-CONSTRUCTION GEOLOGY:________

SURFACE GEOLOGY:________

PREDOMINANT ROCK TYPE (S):________

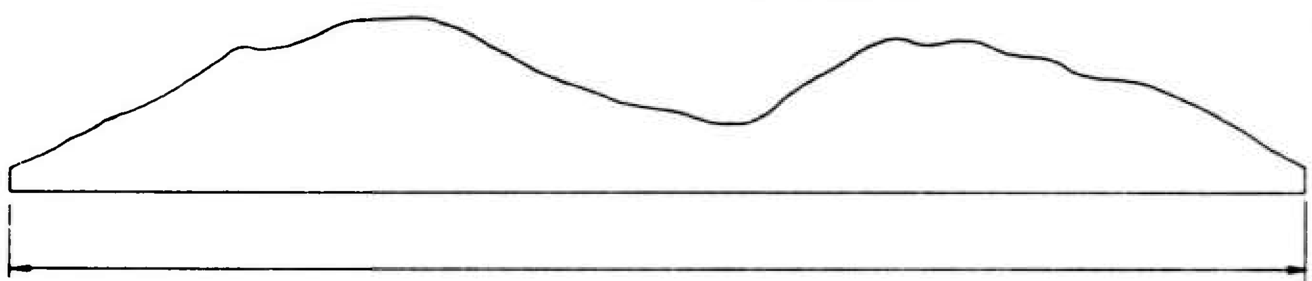
BORINGS:________

LAB TESTS:________

OTHER:________

GENERAL:________

STUDY PROFILE



INDICATE:

1) APPROX. LENGTHS OF STUDY SECTIONS
2) DIRECTION OF DRIVE (S)
3) MAJOR FAULTS
4) LOW COVER ($<$ 2 DIA.)
5) PERTINENT DATA

DATA FOR STUDY SECTION

a) LENGTH
b) BORINGS
c) ROCK TYPE
d) GEOLOGIC STRUCTURE
e) ORIENTATION OF JOINTS
f) JOINT SPACING
g) JOINT CONDITION
h) WATER FLOW
i) FORMATION NAME

Figure 2.1

CASE HISTORY NO: ________ NAME OF TUNNEL: ________ SECTION NO: ________

ROCK STRUCTURE RATING (RSR) EVALUATION:

GEOLOGIC FACTORS:	*	OTHER DATA:	PARAMETER VALUE:	
ROCK TYPE ________	( )	CORE RECOVERY ________	"A"	________
GEOL. STRUCT. ________	( )	RQD: ________	"B"	________
JOINT. ORIENT. ________	( )	OTHER: ________	SUB TOTAL	________
JOINT SPACING ________	( )	________	"C"	________
JOINT COND. ________	( )	________	TOTAL RSR	________
WATER ________	( )	________	TBM FACTOR	
			ADJUSTED RSR	________

* Provide Suffix (3) = Data Defined (2) = Data Inferred
(1) = As-Built Data Used (0) Data Not Given

PREDICTED GROUND SUPPORT:

CALCULATED RIB RATIO (RR) AND ROCK LOAD (Wr) RR = ________
BASED ON ROCK STRUCTURE RATING Wr = ________
RECOMMEND SUPPORT (S):
TYPE: ________ ________ ________
SIZE: ________ ________ ________
SPACING: ________ ________ ________
COMMENTS: ________

ACTUAL GROUND SUPPORT USED:

TYPE: ________
SIZE: ________
SPACING: ________
ACTUAL RIB RATIO (RR) ________
(OR EQUIVALENT) ________
COMMENTS: ________

Figure 2.1 (continued)

spect to those areas in which original data was insufficient to make realistic conclusions, namely: 1) greater variety of tunnel sizes, 2) tunnels using shotcrete or rock bolt reinforcement and 3) mining operations. Mining operations will be treated separately in Section 3. Twenty new civil tunnels were studied bringing the total to 53. These 53 tunnels have an aggregate length of almost 200 miles, constructed mostly in the West and mid-West, U. S. They range in size from 8 feet to 36 feet in diameter. Individual tunnel lengths vary from a few hundred feet to over twenty three miles. They have been driven through a variety of rock types and conditions from uncemented conglomerates, that could barely be called rock, to the hard massive granite of the Sierras, with the need for support varying accordingly. The complexity of ground structure also varies from uniform rock conditions throughout the tunnel to as many as twelve distinctly different geologic sections with faulted and folded conditions.

2.3 SOURCES OF INFORMATION

To acquire the necessary tunnel project records, many agencies were contacted. The problem of support prediction is a common one in the industry and everyone was cooperative in making their records available, if possible. The notable exceptions, significantly, were some recently completed projects where there was a possibility of litigation to settle claims of changed conditions or support requirements. In each case where data was obtained, it was from the owner agency or engineer representative, as their records are generally more complete with regard to geology and

support placement. In addition to making their records available many people gave their personal views of the completed projects, which was helpful in evaluation in cases of insufficient data. The following agencies provided data for the study. Their cooperation was most helpful.

1. U. S. Bureau of Reclamation - Denver
2. U. S. Corps of Engineers - Omaha
3. Department of Water Resources - Sacramento
4. Pacific Gas and Electric Company - San Francisco
5. Metropolitan Water District of Southern California -Los Angeles
6. Sacramento Municipal Utility District - Sacramento
7. Bay Area Rapid Transit District - San Francisco
8. Board of Water Commissioners - Denver
9. Hetch Hetchy Water Supply - San Francisco
10. San Francisco Water Department - San Francisco
11. Granduc Operating Company - Stewart, B. C.

Additional information for several projects was already available from Jacobs Associates in the form of pre-bid geologists reports, site inspection reports and personal knowledge.

The fifty-three tunnel projects investigated were divided from one, up to maximum of 12 study sections, made necessary where marked geologic differences existed between adjacent sections. Approximately 200 sample tunnel sections were developed by this procedure. The table of Figure 2.2 lists the study projects and the general physical features of each. Numbers

CASE HISTORY STUDY PROJECTS

CASE HISTORY NO.	NAME OF TUNNEL	LOCATION	SIZE OF EXCAV. SECTS.		TOTAL LENGTH L.F.	NO. OF STUDY SECTIONS	METHOD OF EXCAV.
			DIMENS.	SQ. FT.			
1	White Rock	Calif.	24x24 HS	480	24,000	2	D&B
2	Divide	Colo.	12x12 HS	130	28,000	1	D&B
3	Spring Creek No. 1	Calif	22 Dia.	380	8,300	4	D&B
4	Spring Creek No. 2	Calif.	22 Dia.	380	4,500	3	D&B
5	Tecolote	Calif.	9x9 HS	70	33,500	12	D&B
6	Glendora	Calif.	20x20 HS	350	32,500	8	D&B
7	Canyon	Calif.	14x14 HS	180	54,000	8	D&B
8	Crystal Springs Bypass	Calif.	13x13 HS/ 13 Dia.	140	17,100	2	D&B/TBM
9	Azotea	N. Mex.	12 Dia.	110	66,000	2	TBM
10	Navajo No. 1	N. Mex.	20 Dia.	310	10,100	2	TBM
11	Navajo No. 2	N. Mex.	19x19 HS	330	25,820	2	D&B
12	Blanco	N. Mex.	11x11 HS/ 11 Dia.	90	45,600	2	D&B/TBM
13	Oso	Colo.	11x11 HS/ 11 Dia.	90	26,700	3	D&B/TBM
14	Starvation	Utah	9 Dia.	60	5,300	2	TBM
15	Water Hollow	Utah	13 Dia.	130	21,600	2	TBM
16	River Mountains	Nevada	12 Dia.	110	20,000	3	TBM
17	Clear Creek	Calif.	20x20 HS	350	56,600	3	D&B
18	Cascade Divide	Ore.	8 Dia.	50	2,100	1	D&B
19	Green Springs	Ore.	8 Dia.	50	4,800	1	D&B
20	Angeles	Calif.	34 Dia.	910	38,800	2	D&B

D&B - Drill and Blast
TBM - Tunnel Boring Machine

Figure 2.2

CASE HISTORY STUDY PROJECTS

CASE HISTORY NO.	NAME OF TUNNEL	LOCATION	SIZE OF EXCAV. SECTS.		TOTAL LENGTH L.F.	NO. OF STUDY SECTIONS	METHOD OF EXCAV.
			DIMENS.	SQ. FT.			
21	Western Pacific Nos. 1 thru 5	Calif.	22x30 HS	600	21,000	5	D&B
22	Castaic Dam Diversion	Calif.	24 H. Dia./ 33 H. Dia.	400/900	3,600	2	D&B
23	Belden No. 1	Calif.	18.5 HS	310	23,600	8	D&B
24	Belden No. 2	Calif.	18.5 HS	310	9,600	5	D&B
25	Pit River No. 4	Calif.	23x22 HS	450	21,300	7	D&B
26	Poe Tunnel (*Partial)	Calif.	23x23 HS	470	*15,100	8	D&B
27	Camino	Calif.	14x15 HS	190	26,500	7	D&B
28	Loon Lake Tailrace	Calif.	18x18 HS	290	20,200	7	D&B
29	Jay Bird	Calif.	14x14 HS	180	21,000	3	D&B
30	Union Valley	Calif.	19x19 HS	320	4,500	2	D&B
31	Butt Valley	Calif.	17x16 HS	240	10,900	4	D&B
32	Caribou No. 2	Calif.	17x16 HS	240	8,700	4	D&B
33	Flathead	Mont.	22x30 HS	600	35,300	7	D&B
34	Berkeley Hills	Calif.	21x21 HS	370	16,200	9	D&B
35	Poe (partial)	Calif.	23x23 HS	470	17,600	5	D&B
36	Balboa Outlet	Calif.	16 Dia.	200	3,800	2	TBM
37	McCloud No. 1	Calif.	17x17 HS	260	11,200	5	D&B
38	McCloud No. 2	Calif.	17x17 HS	260	25,600	9	D&B
39	Lucky Peak Outlet	Idaho	23 Dia.	420	1,160	4	D&B
40	Foster Dam Diversion	Oregon	32x32 HS	910	550	3	D&B

Figure 2.2 (continued)

CASE HISTORY STUDY PROJECTS

CASE HISTORY NO.	NAME OF TUNNEL	LOCATION	SIZE OF EXCAV. SECTS. DIMENS.	SIZE OF EXCAV. SECTS. SQ.FT.	TOTAL LENGTH L.F.	NO. OF STUDY SECTIONS	METHOD OF EXCAV.
41	Cougar Dam Penstock	Oregon	20x20 HS	360	1,830	2	D&B
42	Pomme De Terre Outlet	Missouri	16 Dia.	200	432	1	D&B
43	Wilson Outlet	Kansas	18 Dia.	250	988	2	D&B
44	Kanopolis Outlet	Missouri	17 Dia.	230	2,348	1	D&B
45	Littleville Outlet	Mass.	10x10 HS	90	374	1	D&B
46	N.Fork of Pound Resv.	Virginia	11 Dia.	90	690	1	D&B
47	Worcester Diversion	Mass.	21x21 HS	390	3,700	2	D&B
48	Tenkiller Ferry Outlet	Okla.	22 Dia.	380	557	1	D&B
49	Fort Randall Resv.	S. Dak.	26 Dia./ 36 Dia.	530/ 1,020	10,476	2	D&B*
50	Blue River Resv.	Oregon	24x24 HS	510	1,623	1	D&B
51	Hills Creek Sam	Oregon	27x27 HS/ 18 Dia.	650/ 250	1,150/ 545	2	D&B
52	Harold D. Roberts	Colorado	12x12 HS	130	122,900	12	D&B
53	Granduc	Brit. Col.	15x15 HS	200	54,500	4	D&B

*Kerf cut by coal saw

Figure 2.2 (continued)

1 through 33 were studied during the first year, and 34 through 53 the second year.

2.4 APPLICABILITY OF RECORDED DATA

Prediction based on past experience is quite common and necessary in tunneling, whether it involves excavation progress, ground support or muck handling. This is made necessary by the complex and varying nature of the rock medium in which the tunneler must work. Much of the measured success for a tunneling project is how well we apply the lessons of past experience to new situations. The more variables a problem contains, the more facts are needed for a solution. The possible combinations of geologic factors in determining rock mass characteristics are virtually infinite. One objective of this study has been to simplify the number of factors to those most important in determining rock competency, and to acquire enough factual data through studies of case histories on which to base an empirical prediction method of needed rock support or reinforcement. Assuming tentatively that this is possible, we must recognize the fact that the method cannot be more accurate than the data it is based on. It is necessary therefore to evaluate these data and the methods employed to obtain and record them.

2.4.1 Physical Dimensions and Construction Factors

The most important construction factors in considering requirements for ground support is the size and configuration of the tunnel bore and the direction of drive with respect to the strike and dip of the jointing system

in the rock. A larger opening will require more support than a smaller one in the same ground. Likewise, a flat back or flattened arch will require more support than a semi-circular arch. The orientation of the strike and dip of the rock with the axis of the tunnel will determine whether or not individual blocks or slabs will tend to fall into the tunnel to form a stable back.

Generally, records of physical dimensions are the easiest to obtain and the most reliable. Where neither the pre-construction, nor as-built geology records indicated the direction of the strike and dip an assumption was made based on other factors or an average value assigned to that factor.

2.4.2 Geologic Data

The following geologic factors were determined to be the most important when considering requirements of ground support:

1) Rock type and classification; 2) Rock structure (relative faulting or folding) 3) Joint strike and dip, 4) Joint spacing, 5) Condition of joints, and 6) Ground water inflow.

While other factors are important for determining boreability, drillability, and muck handling, they are not necessarily important to the problem of support.

The sources for obtaining this information in the pre-construction stage are:

1) Boring samples and logs, 2) Surface geology, 3) Geology

reports, 4) Historical geology, 5) Records of nearby projects, 6) Seismic studies, and 7) Laboratory tests.

An attempt was made to use only such data as was available prior to construction in determining Rock Structure Ratings. Only when such information was missing, was as-built data used to augment this determination. The available data was then reviewed for the first 33 case history studies. A table was made indicating what type of data was available with an indication of how well defined it was. This was in turn used to produce a "Reliability Profile" chart indicating the ability to define the six geologic factors shown above from the data available. It was found that for these studies factual data was sufficient to define geologic factors about 50% of the time, varying from 80% for rock type to 25% for joint spacing. In many cases where defining data was missing the study team assumed values on the basis of judgment of available information. Where no information was available for a particular factor an average value was assumed.

The concept of evaluating input data was continued during the second year for the remaining case history studies. This evaluation was incorporated in the data recording form, Figure 2.1. Results were similar for the 20 additional case history studies with higher ratings for more recent projects. The current on-going field studies, which will be described more fully in Section 6, are indicative of this trend toward making more geologic studies in the pre-construction period. When calculating RSR values for the final predition model, the best available data was used in each case,

whether it was pre-construction, as-built or a combination of data.

For many of the tunnels investigated having both pre-construction and as-built geology available, there was a reasonable similarity between the two. This was particularly true for relatively shallow tunnels in simple rock structures. Tunnels in complex folded and faulted structures however, such as the Harold D. Roberts tunnel (case study no. 52), showed a marked disparity between rock conditions projected from the surface and actual conditions encountered in the tunnel.

2.4.3 Actual Ground Supports Used

One question that keeps recurring concerns the appropriateness of using actual supports placed in the past as a guide to a prediction model for the future. Are we merely perpetuating the abuses of over support that sometimes apparently exists because of contractual, monetary, or construction expediency considerations? Or, do the support systems used in the case studies truly reflect the loads carried? After lengthy consideration of this question during this two-year study the facts appear to substantiate use of past experience records if used judiciously.

We know that the support systems investigated are conservative because they have not collapsed. We do not know to what degree each individual case is oversupported, but given enough individual situations, and assuming factor values to be reasonably correct, trends and patterns emerge.

A review of the RSR support graph in Figure 1.2 shows an envelope of points rather than a thin line. We can make the general statement that

the points to the right and above the average curve are more conservative in their load carrying capacities for a given situation than those to the left and below the line. Given enough points and confidence in the method we can eliminate those situations which obviously fall far outside the range of the majority. This will be discussed further in Section 5 where revisions to the prediction model are presented.

One fact should be born in mind; a point outside the envelope does not necessarily imply that too much support was used, merely that the support appears conservative within the limitations of the model. The model considers only normal vertical load with minimal side pressures. Because of the limited nature of some facts available in the case history records, it has not proven practical to include factors such as high in-situ stresses or swelling or squeezing ground. Many of the points above the envelope do in fact represent this type of situation.

By eliminating these points from consideration we can develop an empirical relationship closer to the norm for the majority of situations that are covered by this model. While this relationship is still conservative it does eliminate those extreme cases and is based on the average of the remaining points, not the most conservative. Hopefully, increased use of instrumentation will help to define actual loads more closely in the future.

As mentioned earlier most of the ground support used in tunnels of the original 33 case studies was steel ribs. Only a few sections used rock bolt reinforcement and none were supported by shotcrete. A special

effort was made during the second year to locate examples of rock bolt and shotcrete tunnels applicable to this study. Although use of shotcrete is on the rise in the United States there are still not many completed tunnels available for research analysis. Those that were available were used and one, New Melones diversion tunnel is described later as a field study. Through the cooperation of the U.S. Corps of Engineers office in Omaha, records of several tunnels were made available to the study team. Six of these tunnels as well as the Norad Extension, used as a field study were supported in whole or part by rock bolt reinforcement.

It should be noted that many of the initial sections studied were unsupported. This was done in an effort to define, if possible, the RSR value where supports were considered unnecessary. It was not possible to do this directly and this was found by interpolation and projection. To understand the reason for this situation we must consider the practical aspects of setting supports under conditions of fairly competent rock. Even if it should be determined that supports would be sufficient on 10 foot to 20 foot spacing, it would be impractical because of consideration of blocking, lagging, collar braces, etc. It is common practice to limit rib spacing to about 6 feet, until support is no longer needed. In like manner there are practical limits to rock bolt spacing patterns and shotcrete thickness.

Most of the projects investigated gave a reasonable definition of actual supports used in terms of size, spacing, etc. Some project records gave only approximations or total quantities in pounds where temporary

supports were a pay item. If the tunnel was short and in fairly uniform rock, this was sufficient to develop an average RSR-support relationship. In a longer or more complex project where geologic conditions and supports varied, it was not possible to correlate the two without sufficient detailed data. Where only a total pay quantity of pounds of bolts was recorded, it was impossible to reconstruct the probable bolt pattern used. This accounted, in part, for the lack of such study sections in the first 33 case histories.

2.5 COMPARISON OF RESULTS OF NEW CASE STUDIES TO ORIGINAL PREDICTION MODEL

The first 33 case studies were used to develop the original RSR prediction method. This evolved in stages. At each step, factor values were altered, eliminated or combined. New combined RSR values were computed for each study section and compared to the actual support (RR). These were plotted on a new RSR vs. RR graph and the effects of the changes on the overall pattern were noted.

The procedure differed in the second year in that each new case study added could be individually compared to the existing model. After dividing the tunnel into geologic sections, known data was entered on the forms in Figure 2.1. RSR values were found and corresponding rib ratios (RR) and unit rock loads (Wr) computed. These were used to estimate predicted ground support which were then compared to the actual support system used.

Where discrepancies were found, an attempt was made to explain them through additional record search or discussion with someone familiar with the project. This had the effect of making each case history study in the second year into a modified field study. In general, the correlation of these studies fit the original prediction model. Observation of some of the exceptions contributed to the decision to modify and expand the final model, to be described in Section 5.

The particular items that these investigations highlighted as deserving of additional attention were:

1. Very soft or decomposed rock
2. Crushed and highly fractured rock
3. The aforementioned nebulous zone of minimal support

It is interesting to note that the first two items were also mentioned in the comments of people whose aid was enlisted to evaluate the RSR method.

In reviewing the other objectives of these additional studies the following is noted:

The slightly deficient gap in tunnel size has been corrected in the second year. A check of the 200 total study sections indicates an average excavated cross sectional area of about 300 sq. ft., equal to a circular section 20 foot in diameter or a horseshoe section 18.5 x 18.5 feet. A typical lining would reduce this to a 16 or 17 foot tunnel. There is an even gradation from this average down to 50 sq. ft. (8' diameter) and up to 1000

sq. ft. (36' diameter).

As mentioned earlier, lack of sufficient tunnel data available for either rock bolt or shotcrete reinforced tunnels did not permit the same type of correlation possible for rib supported tunnels. Those points that could be plotted for such tunnel sections were based on the previously assumed approximation of equivalent Rib Ratios and compared favorably to the plots of rib supported sections. These approximations therefore will be maintained at present for the current prediction model.

The original empirical curve was plotted using only drill and blast excavated tunnels and a tunnel boring machine (TBM) adjustment factor curve suggested. This adjustment factor would raise the RSR value to reflect a better condition of the penetrated rock structure normally associated with the boring machine. This factor, which varies inversely with the diameter, was used to determine adjusted RSR values for all TBM study sections not previously used. These points also compared favorably to the existing model and were subsequently used in establishing the new model.

Figure 2.3 shows typical rib supported and rock bolted sections of the Flathead Tunnel in Montana during excavation. This horseshoe shaped tunnel (case study no. 33) was excavated by drill and blast utilizing a Jacobs sliding floor.

FIGURE 2.3

EXCAVATION AND SUPPORT OF FLATHEAD TUNNEL (CASE STUDY 33)

SECTION 3

CASE HISTORIES

MINING OPERATIONS

3.1 INTRODUCTION

This ARPA sponsored research project, as well as others in this BurMines managed series, was directly aimed at maximizing tunneling subsystems for rapid excavation. It has long been realized that the greater the need for support in a particular tunnel, the greater the impediment to rapid excavation. Today, it is not unusual to find a tunnel boring machine (TBM) that is capable of normal progress of 200 feet per day slowed to one quarter of that speed in ground requiring support, and even to 10 feet per day under very adverse conditions. The ability to predict support requirements ahead of the face is obviously of prime importance in the effort to maximize the rapid excavation systems.

Extending these civil concepts of support requirements to the problems of mining was a necessary further application of the RSR for the following reasons. First, ground support is a problem common to all underground work and while the type of support used in mines is often dictated by the nature of the ore body, the need for a support prediction requirement is nevertheless present. Secondly, there are many more miles of mine drifts than civil tunnels and it would help this research effort to be able to tap this wealth of experience.

Except for mine haulage tunnels, general mining operations do not readily lend themselves to neat lengths of geologic uniformity. The Granduc Haulage Tunnel was used in Section 2 as case study no. 53 and the Cajone Haulage Tunnels will be described later in the field studies. However, most mining operations are not readily adapted to the same type of studies made for existing civil tunnels. There is much that can be learned from the wide and varied experience in ground control gained in mining operations. It is fitting that this topic be treated separately.

3.2 COMPARISON OF MINING AND TUNNELING METHODS

In order to achieve a true perspective of the applicability of the RSR concept to mining it is necessary to view objectively the similarities and differences of mining to civil tunnels.

The primary purpose and function of most civil tunnels is transportation from one point to another, whether it be for trains, vehicles, pedestrians, water supply or waste disposal. These tunnels range in size from less than 6' to over 40'. Generally they are permanent installations with permanent lining, designed for the desired function of the tunnel. Most tunnels, whether built for public agencies or private owners, are constructed by contractors who specialize in this type of work. Temporary ground support is generally the responsibility of the contractor as is the choice of excavation method. The aim of the contractor is to complete the excavation and lining as economically as possible within the time and cost framework of

his contract. With one major working area, at the face, and a comparatively large overhead, achieving rapid advance is usually the main economic consideration. To achieve this rapid progress the contractor, within limitations inherent to the individual project, fills the heading with as many men and as much equipment as can operate without mutual interference. The equipment is often purchased or designed specifically for that project and often scrapped on completion. The ground support methods employed are governed by the economics involved, where cost of materials must be weighed against ease of erection and interference with the excavation cycle.

In mining operations the objective is to remove rock and ore from the earth in a reasonably uniform and complete manner. The size, shape and configuration of excavation for the ore body are as varied as nature and the inventiveness of man can make them. Figure 3.1 shows several basic mining methods. Within the ore body, supports are temporary but a safety necessity, and often are designed to last only as long as the life of the mining operation. Controlled caving of the ore body or the gob after removal of ore is common in certain mining methods such as block caving method (e) open stope mining (b) and room and pillar methods (a). Where this is not practical, the excavated area may be back-filled with waste or mill tailings, as in cut and fill methods in a narrow vein (c) or large vertical body (d). It is apparent that ground support with steel sets does not lend itself to these operations in addition to being relatively expensive. Mines use timber in some areas, because of local economies, but many have gone to rock bolts,

Classification of Underground Mining Methods
Elements of Mining (3rd edition), Lewis and Clark: John Wiley and Sons, 1964.

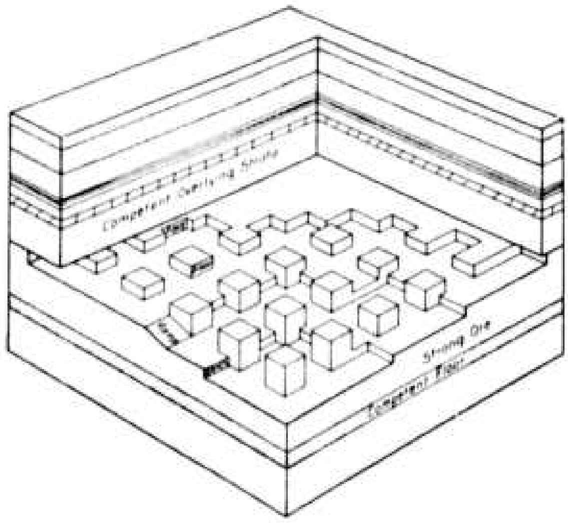


FIGURE 3.1.a

ROOM AND PILLAR METHOD

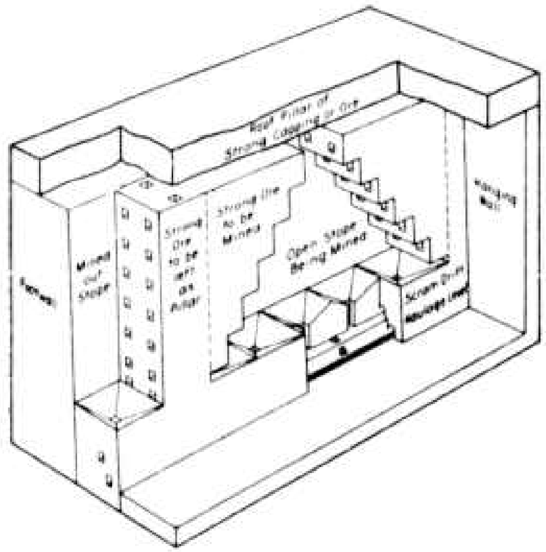


FIGURE 3.1.b

SUB-LEVEL METHOD

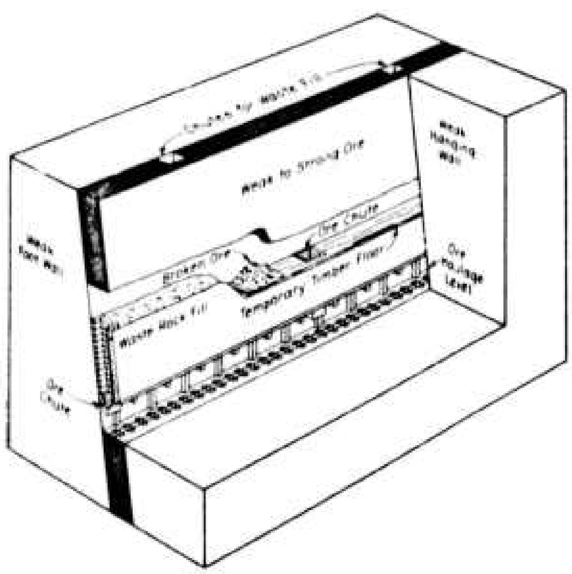
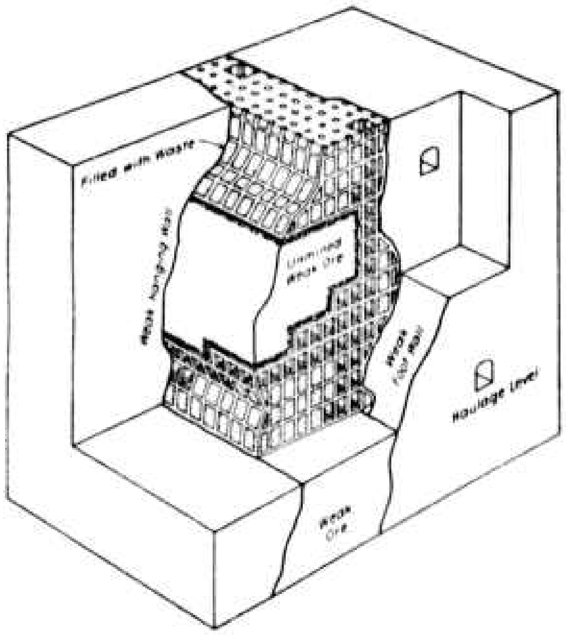


FIGURE 3.1.c

CUT AND FILL METHOD

FIGURE 3.1



TIMBERED SQUARE SET
(WITH BACKFILL) METHOD

FIGURE 3.1.d

BLOCK CAVING METHOD

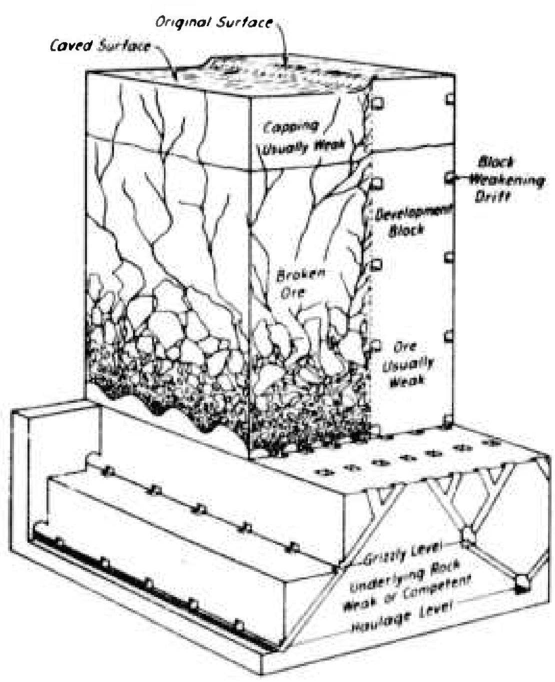
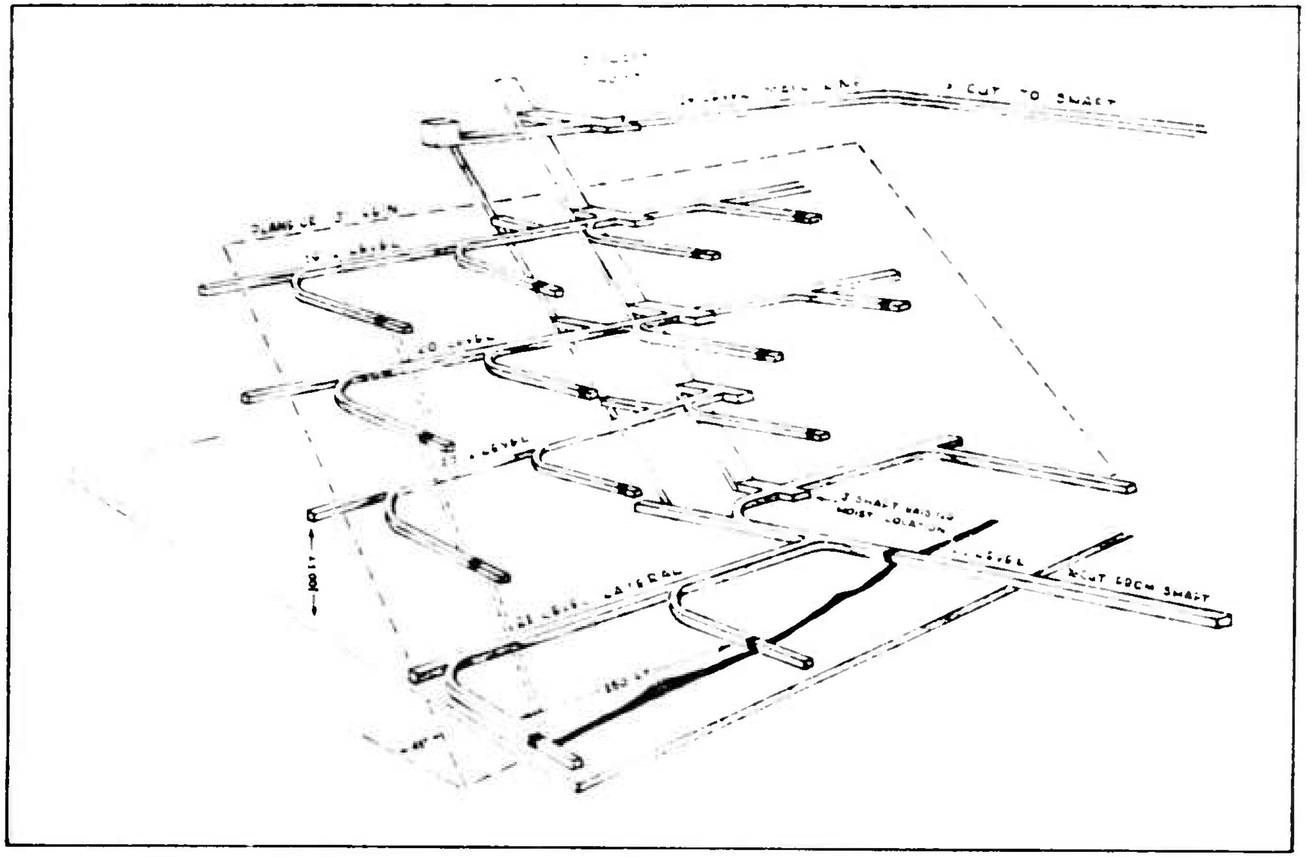


FIGURE 3.1.e

FIGURE 3.1 (Cont'd)

and more recently several mines use shotcrete where applicable. Mining companies either hire miners and operate the mines themselves or contract portions of the work directly with the miners on a crew basis while having service and maintenance personnel on force account.

The mining operations most comparable to civil tunnels are the main haulage tunnels and drifts. Haulage tunnels are generally driven to transport ore from the mine to surface installations such as smelters. They are essentially private railroad tunnels. Examples are the Granduc Tunnel (case study no. 53), the Cajone Tunnels (field studies no. 2 and no. 3) and the Henderson Tunnel of the Amax Henderson Mine, to be discussed later. These haulage tunnels are horseshoe shaped from 14' to 24' in height and width, and are driven and supported very similarly to civil tunnels. More typical of mine tunnels are the drifts that are driven to reach the ore body and to remove the ore to a shaft or portal. A single mine may have many miles of these drifts on many levels, extending over a vertical interval of several thousand feet. Drifts are driven rectangular or horseshoe shape in cross section and generally vary from 8' x 8' to 14' x 14' as determined by the choice of equipment used for driving and hauling. Figure 3.2 shows a portion of the extensive system of drifts the Bunker Hill mine needed to develop the "J vein". This mine is in the Coeur d'Alene Mining District of Idaho, where ore veins are generally narrow and steeply dipping. They are worked at successively lower levels by the general method shown in Figure 3.1c, and the void left by mining the vein is backfilled with waste rock or



Simplified block diagram showing typical conventional development of an isolated ore body.

Reprinted from "Ramp Development of Deep Ore Bodies at Bunker Hill" by Robert L. Russell and Henry W. Zimmerman, The Bunker Hill Company, Kellogg, Idaho

Figure 3.2

mill tailings.

Speed of excavation is not the pressing problem in driving mine drifts that it is in the heading of a tunnel. The work can be performed in many locations simultaneously and scheduled so that a new level of development is ready when the ore has been worked out on the previous level. It is not unusual for two man work crews to drive two headings for maximum efficiency. One drills the round, loads and shoots while the other mucks out the other heading. If support is needed it may be placed by a separate crew. In many mine drifts today the most predominant support consists of three or four rock bolts in conjunction with fabricated steel "mats", about 1 foot wide and 9 feet long. The mats are generally placed across the main jointing planes. Some mines more recently have gone to shotcrete support of drifts. Steel support practice is generally limited to main haulage adits with a long service life or larger openings such as underground shops or shaft entries.

3.3 MINE GEOLOGY

The major problem in predicting tunneling support requirements is knowing the characteristics of the rock mass to be penetrated and how that rock will react with a proposed support system. Surface geologic features and borings currently provide most of this information. Usually this covers only a small percentage of the entire line of the tunnel. If the rock structure is complex, or the tunnel lies at great depth, the geologist can give only an approximation of what the tunneler will find. Long tunnels such as

the Harold D. Roberts Tunnel (case study no. 52), may pass through several different formations, types of rock, and degrees of competency.

Usually the tunneler will pass through a particular rock just once and he is never quite sure what he will find just behind the existing face. In the few occasions where a tunnel is driven parallel and resonably close to an existing one, the uncertainties of geologic conditions are considerably reduced. The Berkeley Hills Tunnel (case study no. 34), driven through the Hayward fault, was completed successfully largely on prior knowledge gained in the nearby Caldecott Tunnels. The geology of the complex layered sedimentary rock penetrated by the Carlin Canyon Tunnels (field study no. 5) is another example of reliable ground support predictions, based on nearby parallel railroad tunnels excavated many years before.

The story of geologic knowledge at a working mine is as different from the two parallel tunnels as they in turn are from the single tunnel. Over the many years of development, the mine owner not only obtains a fairly complete three-dimensional picture of the rock mass (that a tunneler would envy), but he also has gained the experience of miles of drifts in which to judge his support requirements. The biggest unknown is whether the vein will widen out or narrow at the next deeper development level. Even faults, like bad habits, can be recognized as drifts cross and recross them. Most large mines have staff geologists and draftsmen who produce detailed drawings of the mine, level by level. Most mines maintain elaborate three-dimensional models which are invaluable for obtaining an overall picture of conditions and help in planning future work. In areas such as the

Coeur d'Alene Mining District of Idaho there are several large operating mines in close proximity and the geologic knowledge gained by each producer augments that of the others. Much overall knowledge of rock behavior and ore mineralization can be gained in this way.

However, the need for reliable ground support prediction is needed in mining when either developing a new mine or when expanding an existing mine into new and relatively unknown areas. The degree of experience with ground support gained under known conditions through years of mine development in one area, can rarely be duplicated in other mines. Thus the miner has much to gain, and to contribute, in this particular field of study.

3.4 SITE VISITS TO OPERATING MINES

During the past year a joint study team consisting of a member of Jacobs Associates and the Technical Project Officer of the Bureau of Mines visited a total of seven mines and one mine haulage tunnel. Five of the mines were in full operation, and two were in the development stage. While the main objective of these visits was to study the ground support methods used, the team also observed typical ore mining procedures in the working mines. In each case the ground support problem at the individual mine was discussed with one or more members of the staff. A brief description of each of these sites follows:

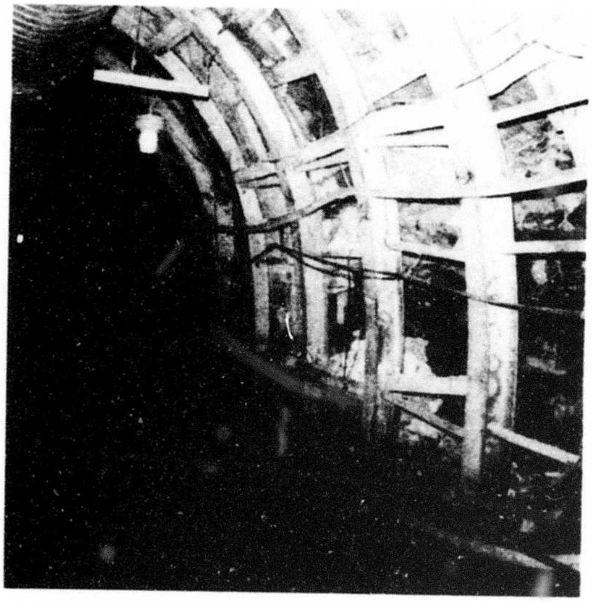
3.4.1 Henderson Haulage Tunnel

This tunnel is being driven by drill and blast methods beneath the

continental divide in Colorado by a contractor to Amax, the Dravo Corporation. It is horseshoe shaped, 18' x 18' excavated, and will be ten miles long, connecting the Amax Henderson molybdenum mine with the Henderson Mill. Originally it was thought to be a good prospect for a field prediction study. The study team had the unique opportunity of discussing the project with the owner, the contractor and the geologist who performed the original exploration. In addition they visited the tunnel site during construction when approximately 2 miles had been driven. Unfortunately, this tunnel is representative of the worst difficulties of geologic prediction. It is in the same general area as the Straight Creek and Harold D. Roberts tunnels. The rock structure is faulted and folded; the tunnel is deep, averaging 2500 feet and up to 5000 feet below the surface across the continental divide; surface outcrops are scarce. The rock found in the three miles of tunnel driven by June 1973 bears only token resemblence to that on the surface and has required more support than anticipated. Support is mainly provided by steel ribs, though in isolated short sections shotcrete has been used, (separately or supplementing steel ribs). To further complicate the problem, several areas of squeezing ground have been encountered requiring placing invert struts and 8" ribs instead of the 6" ribs used elsewhere. Figure 3.3 shows a typical steel supported section in this tunnel.

3.4.2 Amax Henderson Mine

This mine is being developed to use the same block caving techniques that has proven successful at the Climax Mine. The molybdenum ore body



TYPICAL STEEL RIB SUPPORT IN HENDERSON TUNNEL

FIGURE 3.3

HENDERSON MINE – HEAVY RIB SUPPORT AT VASQUEZ FAULT

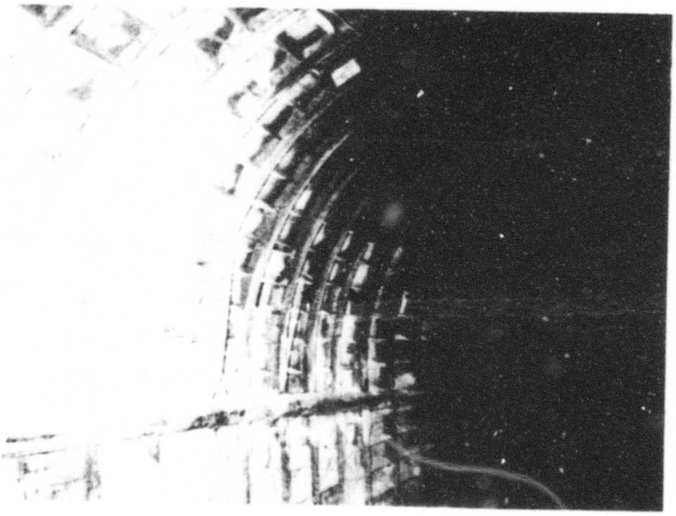


FIGURE 3.4

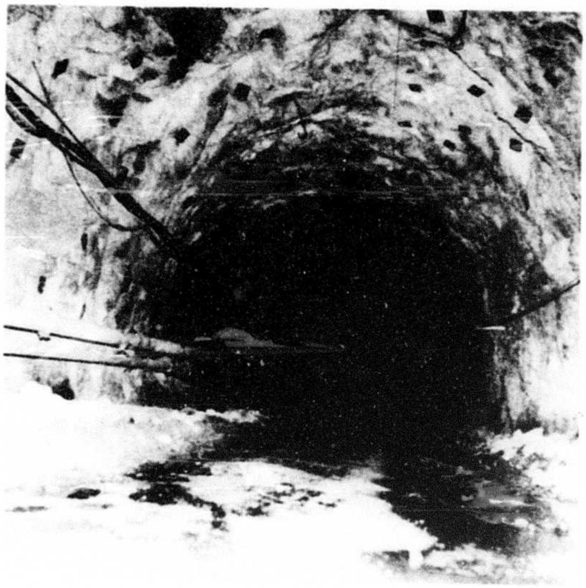
beneath Red Mountain near Empire, Colorado, varies from 400 to 800 feet in thickness. It is contained in a sequence of rhyolite porphyries that have invaded Silver Plume Granite. Many miles of haulage drifts, slusher drifts, finger-raises and cross-cut drifts must be driven before caving of the ore can begin. In June 1973, about 10 miles of such development work were completed along with two (of the three) shafts, each about 2400 feet deep.

Drifts are driven hoseshoe shape about 14' by 14' using rubber tired equipment; carriages mounting three drills and articulated mine-type muckers with 5 cu. yd. front end buckets. Muck is dropped down chutes to lower level with rail mounted muck trains pulled by diesel locomotives. Most of the drifts are unsupported. One section, through the Vasquez Fault, required steel ribs at two-foot centers with solid steel lagging. (See photo Figure 3.4) Fortunately, this was an exceptional case. In other areas requiring support, rock bolts or a 2" thick shotcrete layer have been used, as shown in Figures 3.5 and 3.6. Shotcrete has proven so successful that it is now used almost exclusively where support is needed in drifts. Underground warehouse and shop areas are also covered with shotcrete and painted white.

In some areas, high in-situ stresses pop slabs from the vertical sides of the hoseshoe shaped drifts until an almost circular shape is produced as a naturally stable shape.

3.4.3 Lucky Friday Mine

This mine is fairly typical of a deep mine in the Coeur d'Alene



HENDERSON MINE –
TYPICAL ROCK BOLT
REINFORCED DRIFT
SECTION

FIGURE 3.5

HENDERSON MINE –
SHOTCRETE SUPPORT
IN SUMP DRIFT

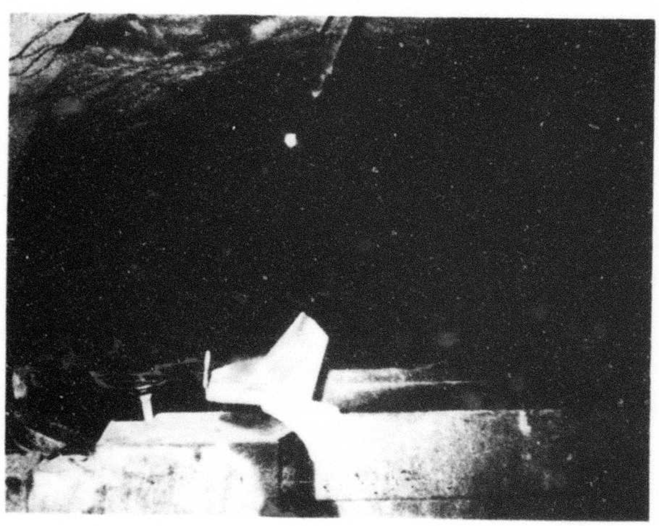


FIGURE 3.6

Mining District of northern Idaho. The following general description will apply to the other mines and only significant differences will be noted.

The ore is found in mineralized veins and consists of lead, zinc, silver and copper, in order of abundance, with small amounts of other minerals. Lead in the form of galena, leads all other minerals combined 3 to 1. The veins vary in thickness from 1 to 5 feet and occasionally to 20 feet, and dip steeply. Mining in the Coeur d'Alene dates back to the 1880's and the upper levels of known veins are depleted. Most ore veins mined today are relatively deep, some over 7,000 feet below the surface.

Access to the Lucky Friday mine is typical of many mines in the area. A work area was leveled off on the side of the hill and an adit driven to the ore vein. A vertical shaft is then sunk to the desired working levels and development drifts driven to the vein. The ore is mined horizontally out about 150 feet on either side of the stope service raise using a slusher to pull the broken ore to the raise chute leading to the drift. On completion of mining a horizontal slice, hydraulic backfill of tailing fines is pumped into the void where the ore had been. When this is sufficiently compact, the next higher working level is excavated using the fill as a base. As the ore is being removed, the shaft is deepened to the next development level, usually 200 feet below. This next level is then developed so that it is ready for mining when the previous level has been mined out.

In the Lucky Friday mine, all drift excavation equipment is presently rail mounted. An overshot mucker loads a single car which is taken to

the shaft, dumped and returned to the heading. The drifts are driven rectangular about 9' x 9'. The country rock is Revett quartzite; almost white, hard, blocky to closely jointed, with joints dipping steeply. The mineralized veins are very pronounced and sharply defined. Where the rock is closely jointed, support is provided by rock bolts and fabricated steel mats as shown in the photo, Figure 3.7. In this mine, it was evident how this support system could be used to its full advantage. In drifts perpendicular to the strike, as in Figure 3.7, the mats in the arch are placed parallel to the centerline. Where drifts are parallel to the strike, mats in the arch are placed across the drift. In both cases sidewall mats are about 45° to the horizontal, with top toward the heading, and bottom overlapped by the previous mat. Using 4 bolts per mat gives a bolt pattern about 3' x 3'. In some of the other mines using this type of support, bolts and mats were placed in a regular pattern without regard to the strike and dip of the joints.

3.4.4 Crescent Mine

This mine is similar in many respects to the Lucky Friday, being largely in Revett quartzite and utilizing the same support method of rock bolts and mats. In deeper levels of this mine, the excavation equipment now used is generally rubber tired. The drill carriage mounts two drifter drills and mucking is by a front end load-haul-dump unit.

The 4000 foot long main haulage adit is at elevation 2800 and was excavated in 1928. Mining has been carried to the 3900 level (1100 feet below sea level) and ore is now being mined from the 4100 level (1300 feet

LUCKY FRIDAY MINE –
TYPICAL ROCK BOLT
AND STEEL MAT
SUPPORTED DRIFT

FIGURE 3.7

STAR MINE –
UNTYPICAL DRIFT
DRIVEN BY TUNNEL
BORING MACHINE

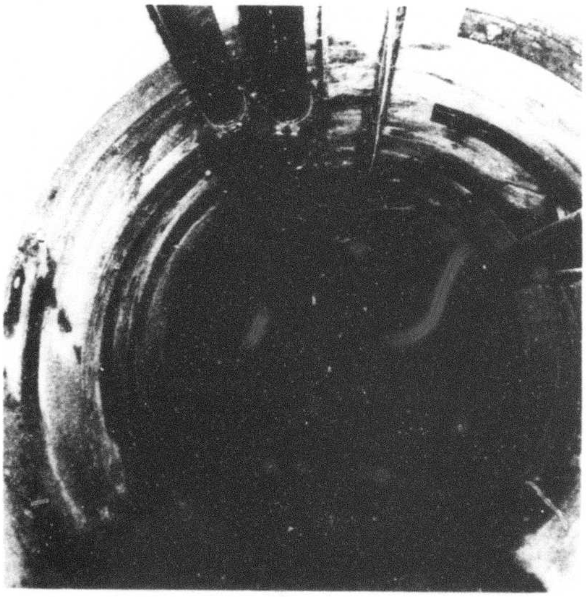


FIGURE 3.8

below sea level). Development work is being carried out on the 4300 level, (1500 feet below sea level). At unventilated levels the temperature is over 90° and humidity almost 100%.

3.4.5 Bunker Hill Mine

The Bunker Hill Mine in Kellogg is the largest in the Coeur d'Alene district. As in the case of several other mines, it has grown by consolidating properties of several smaller mines for more efficient operation. The main access adit is the Kellogg Tunnel, 9000 feet long, driven between 1893 and 1905. Inclined shafts, roughly parallel the dip of the ore veins at about 50° to the horizontal. Ore, men and materials travel these inclined shafts between the adit and lower mining levels. The hoist, as in many of these mines, is housed in an underground hoist room. With increasing depths of mining, the hoists and rooms have grown over the years. The latest, installed in 1945, is housed in a semi-circular arched room. The 40' span is supported by 15" ribs @ 5' centers.

Drifts are approximately 9' x 9', supported where necessary with rock bolts and mats. The mine reports over 100 miles of drifts. The Bunker Hill mine is changing a portion of its mining to a trackless system with 15° ramps to connect the lower working levels; two cu. yd. loaders are used for these longer runs, as compared to the 1 cu. yd. loaders used previously (6).

On our inspections, a thick, more flat lying vein of high grade zinc

ore in this mine was being excavated by an overshot loader instead of the usual slusher. Support in this area is by pre-cut timber square sets.

3.4.6 Star Mine

Although in many respects the Star Mine at Burke is similar to other Coeur d'Alene mines, there were several unique features of particular interest observed in the mine visitation. This is the deepest mine visited, with current mining operations 7500 feet below the surface. The rock temperature at this level is about 110°F. Refrigerated air conditioning has reduced the ambient air temperature to 76° F.

In 1969 the Star Mine experimented with a tunnel boring machine for driving drifts. The rock through which the machine was driven was hard blocky Revett quartzite with an average unconfined compressive strength of 29,000 p.s.i. The first section driven by TBM was about 100 feet. Except where blocks had fallen out, the typical smooth bore produced by the machine is evident in Figure 3.8. Rock support in this area is by rock bolts and mats on both sides and perpendicular to center line, each mat is held by three bolts. Mats are 4' on centers giving a bolt pattern of 4' x 4'.

It was found necessary to modify the TBM to overcome muck handling problems and then used to drive a second section about 200 feet long. The major problems encountered concerned muck size. Because of the hard, brittle nature of the quartzite, blocks 6" to 9" fell out of the face. These damaged the lubricating system and the scrapers and scoops which were not designed for such large cuttings. Also, in the second section more fallout

behind the face was experienced. Mine representatives felt that machine progress and costs were reasonable when the machine was working, but that there would have to be many changes made to tunnel boring machines to be adaptable to mining in this type of ground.

The rock at this depth also displayed typical Coeur d'Alene Mining District evidence of high in-situ stresses in the form of squeezing rock and rock bursts. Blocking and wedging with considerable side squeeze on the timber cap is shown in Figure 3.9. In another area, the invert heaved about 1 foot after excavation and had to be recut. Figure 3.10 shows a drift side-wall rib where a large rock burst had occurred. Note the effect this burst had on the rock bolts and steel mats. In some areas, rock slabbed off the sides of the rectangular drifts to produce a more stable circular shape.

In 1967-1971, new No. 4 shaft and hoisting facilities were constructed at the Star Mine. The new underground hoist room on the adit 2000 level is horseshoe arch shaped 96' long 40' wide and 40' high, is supported with rock bolts and 6" to 8" of shotcrete as shown in Figure 3.11. In addition, nearby transformer and slurry pit rooms, each about 20' wide arched back are supported by 4" of shotcrete. The only evidence of shotcrete cracking found on visitation was at sharp exterior corners and a very pronounced crack where the country rock in the shaft area is crossed by a thin ore vein.

3.4.7 Caladay Mine Development

Work on this new mine development began in 1969 and to date consists of about 5000 feet of 12' high by 9' wide horseshoe shaped access adit,

STAR MINE –
EXAMPLE OF SIDE
SQUEEZE OF ROCK

FIGURE 3.9

STAR MINE –
EXAMPLE OF EFFECT
OF ROCK BURST

FIGURE 3.10

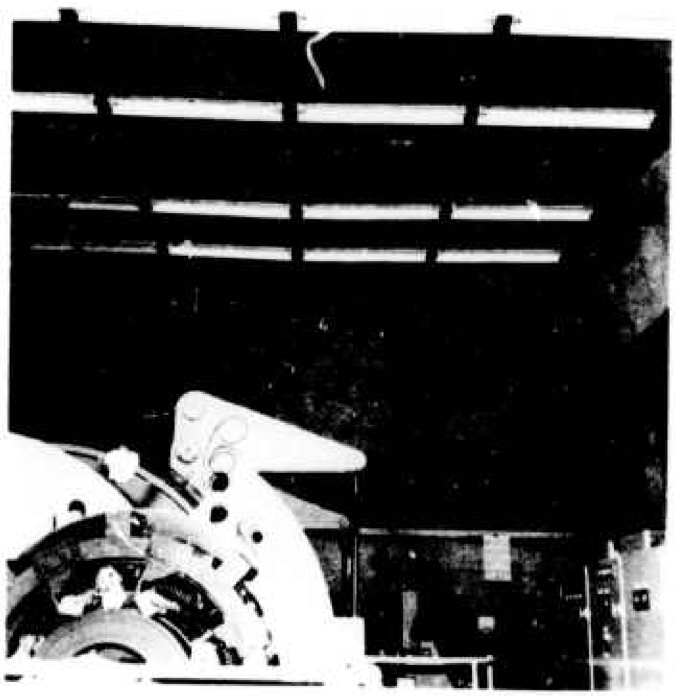


FIGURE 3.11

STAR MINE –
UNDERGROUND HOIST ROOM
SUPPORTED BY SHOTCRETE

auxilary drifts at the adit level, and an underground hoist room. The main adit is in the Wallace and St. Regis formations consisting of argillite and quartzitic fine grained metamorphic rock, less jointed than the Revett.

Most of the access adit is unsupported. Only a portal section has timber sets and lagging. About 10% of the adit is supported by shotcrete, reported 2" thick. Shotcrete was also used to support development drifts where necessary. This was the only mine visited in the Coeur d'Alene district where extensive shotcret support of adits and drifts had been practiced, although other mines have used it in special situations. Attempts to use shotcrete in an area covered by wire fencing and rock bolts resulted in failure of the shotcrete by not adhering to the mesh and yielded poor results. When used on bare rock, shotcreting was successful and has stood up quite well.

The underground hoist room is 94' long, 54' wide and 54' high with a flat back, rock bolted and covered by 6" to 12" of shotcrete. It is the largest underground hoist room in the area.

3.4.8 Pine Creek Mine

Pine Creek Mine is located near Bishop, California on the eastern slope of the Sierra Nevada. It is one of the largest tungsten deposits in the United States and is also a source of molybdenum and copper. The ore body, a tactite, is about 4000 feet long, 3000 feet in vertical depth and up to 100 feet wide. Drifts for mine development have penetrated through surrounding contact zones of quartz monzonite and granite with intermingled veinlets of

quartz. Rock units are massive with few visible joints. Not even when passing from one type of rock to another is a plane of weakness apparent although the transition is usually sharp and distinct. This massive rock permits an open stope mining method in that large flat back stopes are carreid in an under-cut and mill hole mining method. Stopes are 60 to 80 feet wide and 80 to 100 feet long with few comparable sized pillars between.

Most of the drifts are driven without support. For instance, in the Easy-Go-adit, the main mine haulage level, only 600 feet are supported by steel sets out of a total of 12,000 feet. The Easy-Go adit is presently below mining in the ore body with service raises to drifts at various working levels above. As the stopes are mined at successively higher levels, huge open stopes hundreds of feet high remain. This has created a strain on some intervening pillars in the vicinity of these stopes, which in places is evidenced by the peeling of large thin slabs from the rib.

3.5 CORRELATION OF MINING OPERATION SUPPORT

The amount of time available for detailed review of support practices along the miles of mining adits and drifts visited did not permit a comprehensive classification into geologic sections. Because of the additional three dimensional complexity of these extensive drift systems, it would take a long time to gain familiarity with the entire mine layout to separate out similar geologic-support sections. In the mines visited it is possible to generalize a range of RSR values with comparison to supports used.

For the Coeur d'Alene mine drifts driven in Revett quartzite, and where support was required, a range of RSR values was estimated at between 44 and 57. The rock bolt spacing observed varied from 3' x 3' to 4' x 4'. To show this on the RSR vs. RR graph it was necessary to find equivalent rib ratios for these bolt spacings. Using the relationship suggested for rock bolts in Section 1, the weight of rock supported, and the spacing for 3/4" bolts, is:

$$S = \sqrt{\frac{13.5}{Wr}} \qquad \text{or} \qquad Wr = \frac{13.5}{S^2}$$

where Wr is the unit rock load in kips per sq. ft.

and S is the bolt spacing in feet.

This can be used to estimate a rib ratio capable of supporting the same weight of rock:

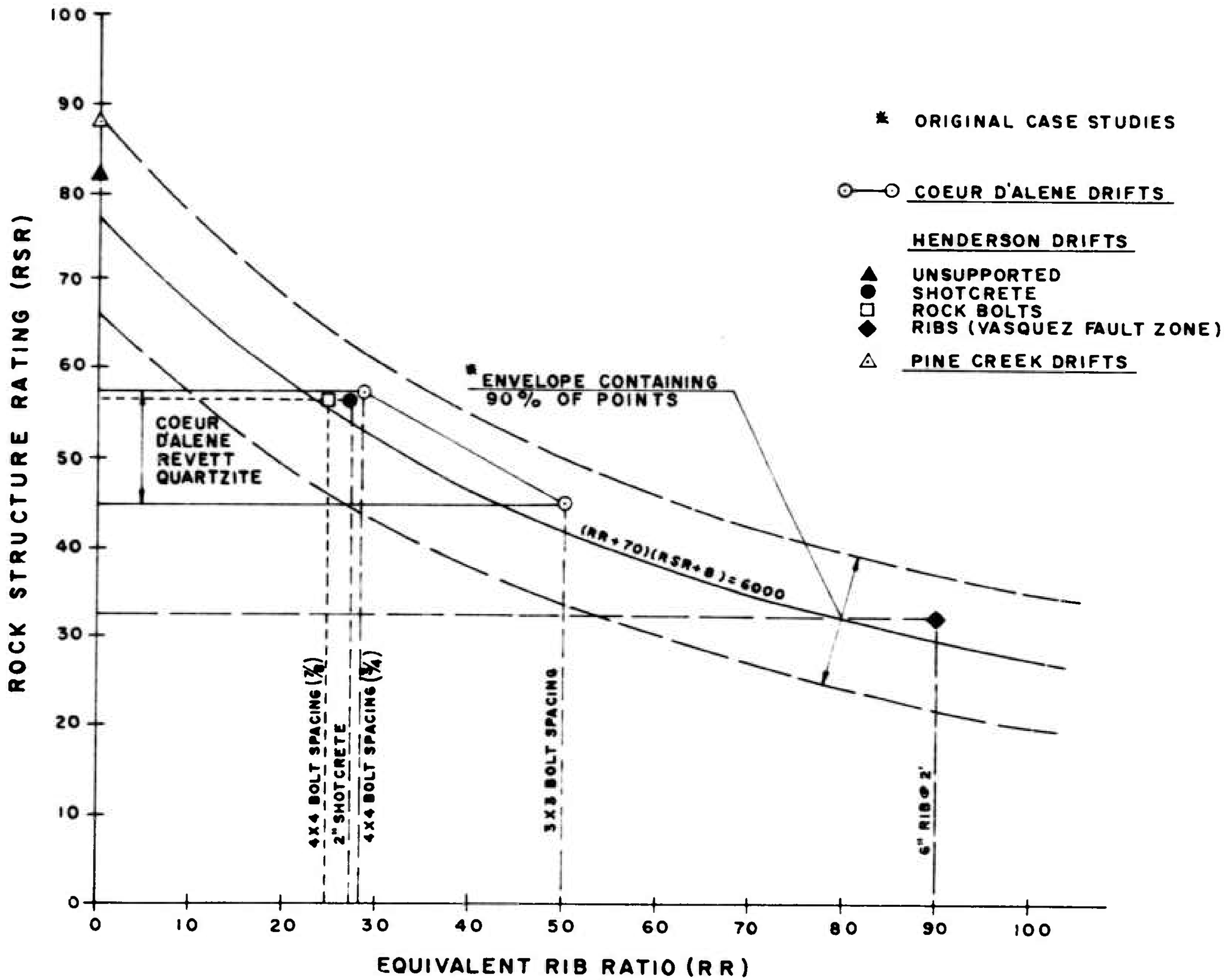
$$Wr = \frac{D \times RR}{302} \qquad \text{or} \qquad RR = \frac{302\ Wr}{D}$$

where D is the average of the height and width

of the drift in feet.

In the case of the Coeur d'Alene drifts, this gives equivalent RR of 50 for the 3 x 3 pattern and 28 for the 4 x 4 pattern. Figure 3.12 shows this range of RSR and RR values as compared to the original model envelope.

In the case of the Henderson mine, three RSR values were estimated; 1) for rock in areas not requiring support (RSR 83), 2) for areas requiring rock bolt or shotcrete support (RSR 56), and 3) for the area of the Vasquez fault requiring rib support (RSR 32). To find the equivalent rib ratio for the shotcrete the weight of rock supported is found by using the suggested



MINE DRIFTS

Figure 3.12

relationship:

$$t = 1 + \frac{Wr}{1.25} \qquad \text{or} \qquad Wr = 1.25\ (t - 1)$$

where t is thickness of shotcrete in inches.

This equivalent RR is 27 and for rock bolts 4' x 4' is 25. The RR for steel ribs at the fault is 90. These have been plotted on the graph, Figure 3.12.

The Pine Creek mine drifts were essentially unsupported, except for occasional rock bolts, and the estimated RSR value of 88 bears this out.

It is interesting to note the relatively more widespread use of rock bolt support in mining, as compared to civil tunnels. Based on the case history studies of civil tunnels investigated, the use of rock bolts has been limited to relatively competent rock, RSR>57, where minimal support is suggested. The mining industry has apparently been successfull in using rock bolts in rock structures with an RSR value of 44. This value would fall in the medium support requirement range.

It appears that good correlation exists between the mining examples shown on Figure 3.12 and those used to establish the RSR model.

Unfortunately, more data required for RSR determinations are not readily available from most mining operations. The records kept by mining geologists and draftsmen are primarily for ore search and planning mining operations. The type of quantitative data required for determining the geologic parameters of RSR can best be found in most mines by visual observation. Since most mine drifts are not lined, it is possible to observe the rock even

in drifts more than 50 years old (provided it has not been altered by weathering).

A major advantage for using data collected from mines concerns the unresolved question of oversupport that exists in some civil tunnels. The mine operator, acting as general contractor, has no financial or contractual advantage in using more support than necessary. It is obvious that the actual support used represents his best judgment of the required ground support. It would seem that additional research investigation along this line in the future could be beneficial to both the mining and tunneling industries.

SECTION 4

INDUSTRY EVALUATION OF RSR CONCEPT

4.1 INTRODUCTION

Improving the state-of-the-art in tunneling is a continuing challenge to those involved in underground construction. New methods and procedures are usually evolved over a relatively long period of time as compared to advancement in other types of construction. This is probably due to the fact that tunneling deals with a variable physical medium - the rock structure - whose physical properties are not only extremely varied, even under closely controlled samplings, and which in most cases is virtually unknown at time of penetration. This hovering of the unknown tends to make "non-believers" of many, with individual experience highly valued. At best, it leads to a reluctancy in accepting any change in methods which does not show a high probability of success. Consequently, one of the major obstacles to overcome in the advancement of any new technique dealing with tunnels is obtaining the general approval and acceptance by industry. Regardless of the concept's technical merit, it could contribute nothing unless this acceptance is achieved. The proposed ground support prediction model is no exception. In recognizing this; ARPA, through its agent the Bureau of Mines, has emphasized this requirement as an important aspect of the present research effort.

This section of the report deals with initial industry evaluation of the ground support prediction model. It sets forth and discusses those various comments, suggestions, criticisms, advantages and disadvantages

expressed by different disciplines; all of which are relevant to possible acceptance and use of the concept by industry. Although the discussion relates primarily to civil applications, the basic principles apply equally to the mining industry. In the latter case however, the overall objectives and requirements of tunneling operations are somewhat different than civil construction. This is discussed in Section 3 of the report.

4.2 METHOD OF APPROACH

Various techniques which would be appropriate for soliciting industry evaluation of the RSR concept were reviewed with the Technical Project Officer. Personal interviews, essay, simple 'yes - no' type questions, multiple choice or preference statements, specific or general comments, and other possibilities were examined. Each technique was considered with respect to the complexity of the subject matter, the amount of time and effort which would be required for individual responses, whether or not comments or answers could be realistically correlated and evaluated, and lastly whether or not they would generate sufficient interest so as to obtain a representative number of responses from industry.

Although a general evaluation of the RSR concept was of concern, it was realized that it would be very difficult to propose direct specific questions without giving some consideration or qualification of the many other factors which could have or may have affected a particular tunneling situation. Valid but opposing answers could be given for the same question depending upon the individual's interpretation of the intent and scope of the

subject and his particular background or area of interest.

It was decided that a general 4-part questionnaire would be the best approach. Several sample questionnaires were prepared using different formats and phrased questions. These were reviewed by various members of the study team and eventually finalized in the form shown on pages 4-4 through 4-9. (The indicated answers shown on the questionnaire are discussed later). The questionnaire includes several answering modes and covers a variety of subjects pertinent to ground support determination. The final questionnaire represents a compromise between an exceptionally long questionnaire that would be required to cover all aspects of the problem, and which would probably be unduely burdensome on the respondent, and a short one which would not provide sufficient information for meaningful results.

The requirement was to obtain a minimum of twelve representative evaluations from industry, including responses from groups representing engineers, geologists, owners and contractors. Potential candidates from each discipline were first contacted to see if they would be interested in participating in the study. In nearly all instances the reply was affirmative. This excellent cooperation was probably due to: 1) the general wide-spread interest and concern with ground support problems, and 2) the natural desire of expressing one's opinions on a controversial and complicated subject. Many candidates were of the opinion that an effort to formulate a better method of predicting ground support (not necessarily the RSR concept) was long overdue and that they had in the past endeavoured to set down some

ROCK STRUCTURE RATING CONCEPT EVALUATION

I. General

1. Predicting ground support involves consideration of many factors or criteria drawn from different disciplines. Please rank the following with a weighted % (on a scale of 100%) as to the most frequently used criteria on which you have based your past prediction of ground support.

Pre-bid geology	41 %
As-built geology (nearby projects)	12 %
Past Tunneling experience	19 %
Personal judgement	14 %
Empirical relationship	5 %
Rules-of-thumb	3 %
Theoretical analysis	4 %
Others	2 %
	%
	100 %

2. To establish a correlation between pre-bid geology and ground support would you: (Check most appropriate choice) 75 % a) Include or make allowance for all available geologic information. 25 % b) Use a general approach considering only major geologic factors.

3. In your opinion, what is the minimum geologic data that should be provided in the pre-bid period for the purpose of determining tunnel support?

(See Appendix A)

4. Rank in order of preference (1st, 2nd, etc.) the following investigation techniques which you believe provide the most meaningful information for predicting ground support (assume amount of detail provided by each to be compatible with present day investigation capabilities).

Vertical Borings and Logs	1
Surface Geology	2
Historical Geology	3
Seismic Surveys	4
Laboratory Testing of Samples	5
Other	6

5. Do you believe that the state-of-the-art for making geological investigations is adequate to provide information needed to make a reliable prediction of ground support?

Yes 47% No 53%

6. Should the projection of surface geology to tunnel grade be provided in pre-bid documents?

   Yes 74% No 26%

7. Should the type, spacing and locations of anticipated support be included in pre-bid documents?

   Yes 74% No 26%

8. Supports are sometimes installed for reasons other than geological considerations. In your opinion what percent of support is placed for the following reasons?

Actual ground requirements	48 %
Potential safety hazards	25 %
Expedient to tunnel driving	13 %
Construction methods	8 %
Other considerations	6 %
	%
Total Support Installed for typical tunnel project.	100 %

9. Additional comments on part 1. General (See Appendix A)

II. Geologic Factors

1. The need for ground support is dependent on and/or related to, various geological factors or conditions which individually or collectively affect the physical quality of the rock structure. Rank the following with a weighted % (on a scale of 100) as to the most important factors to be considered in describing the quality of a rock structure with respect to its need for support.

Geologic Factor	Symbol	Weighted Values
Rock Type-Lithologic Classification	(RT)	12 %
Joint Orientation-Strike and Dip	(JO)	11 %
Degree of folding or faulting	(RF)	13 %
Rock Properties-Hardness etc.	(RP)	8 %
Joint pattern-Spacing & Orientation of fractures	(JP)	20 %
Geologic Structure	(GS)	8 %
Condition of joint surfaces	(JS)	8 %
Ground water inflow	(WF)	9 %
Weathering or alteration	(WA)	9 %
Other	( )	2 %
		100 %

ROCK STRUCTURE RATING CONCEPT EVALUATION

2. The effect of geologic factors on the support requirement is usually dependent on other characteristics of the rock structure. In your opinion, which of the factors shown in 1-above must be considered collectively to properly describe their effect on the support requirement. Please indicate grouping of factors by symbol (i.e. ground water inflow and condition of joint surfaces - WF+JS -- etc) in the left hand column. Show in the right hand column the weighted value you would assign to each grouping with respect to their combined effect on the support requirement.

Geologic Factor Grouping	Relative effect on Support Requirement
RP→RT	12 %
JO→JP	15 %
WF→WA	6 %
WF→JS	8 %
Others	59 %
	100 %

3. Various descriptive and quantitative terms have been used to define rock properties or geologic conditions which affect the rock structure and which are considered in making predictions of ground support. Within the general context of support determination, please, indicate your preference (1st, 2nd, etc) as to most appropriate means of describing the following geologic factors.

Rock Type

a.	Igneous-Sedimentary-Metamorphic	1
b.	Classification by subdivision and formation	3
c.	Composition, texture, color, geological age etc. in addition to info in (b)	2
d.	Other ______	4

Geological Structure

a.	Massive-intensely folded or faulted etc.	1
b.	Origin and sequence, geologic age, etc.	2
c.	Other ______	3

Joint Spacing (Predominant Set)

a.	Descriptive (Massive, blocky, intensely jointed, etc.)	2
b.	Quantitative (2", 2" - 6", etc.)	1
c.	Other ______	3

Joint Condition

a.	Descriptive (fresh, weathered, stained, etc.)	2
b.	Quantitative (i.e. 1/4" wide with clay gouge)	1
c.	Other ______	3

Ground water inflow

a. Descriptive (Damp, Light Flow, etc.) 2
b. Quantitative (Anticipate about 50 gpm/1000 L.F.) 1
c. Other ______ 3

Mechanical Properties of Rock Material

a. Descriptive (Medium to hard limestone) 2
b. Uniaxial Compressive Strength (i.e 18,000 psi) 1
c. Other ______ 3

4. Additional comments on Part II Geologic Factors

(See Appendix A)

III. Support Prediction Model

Jacobs proposed prediction model (RSR concept as described in the R. E. T. C. paper on page 9) rates the competency of a rock structure on a numerical scale by evaluating three general parameters, each with respect to several geologic factors and where applicable with respect to each other. RSR ratings were determined and correlated with actual support installations for approximately 120 sample tunnel sections. Empirical relationships were developed which identifies typical support installations with anticipated rock conditions. (See RETC paper presentation (pages 9 thru 16) previously mailed to you).

1. Do you believe the most essential geologic factors have been included in the RSR evaluation? Yes 92% No 8%

2. In your opinion, what additional factors should be included?
(See Appendix A)

3. What relative values would you assign to Parameter "A" 31 Parameter "B" 45 Parameter "C" 24 (See Appendix A of R.E.T.C. paper)

4. Do you believe the weighted values assigned to specific combinations of geologic factors and conditions as shown on tables for Parameters "A", "B", "C" reasonably reflect differences in support requirements?

Yes 74% No 26%

ROCK STRUCTURE RATING CONCEPT EVALUATION

5. Do you believe that pertinent features or physical condition of rock structure can be properly identified on a numerical scale?

   Yes 88% No 12%

6. Do you believe that an empirical relationship between geologic factors and support requirements can be developed which would be adaptable to most rock tunnels?

   Yes 93% No 7%

7. Rate the following in order of preference (1st, 2nd, etc.) as to type of information you would most heavily rely on in developing a support prediction model.

Improved investigation techniques	1
Empirical relationships based on past experiences	2
Theoretical analysis of rock mechanics	4
Rules-of-thumb	6
Insitu testing	3
Data Banks	5

8. Additional comments on part III Support Prediction Model

   (See Appendix A)

IV. Acceptability of Proposed Rock Structure Rating

Any proposed scheme of rock structure classification for support prediction must ultimately have industry acceptance.

1. Please rate in order the segment (s) of industry you believe would most benefit from any concept of Rock Structure Rating.

Federal or State owner agencies	1
Private owners, i.e. utilities	4
Owners A & E representatives	3
Design engineers	2
Geologists	6
Contractors	5

ROCK STRUCTURE RATING CONCEPT EVALUATION

2. Do you believe such a concept would improve or worsen the following:

	Improve	No Effect	Worsen
Owner-engineer relationship	70%	25%	5%
Owner-geologist relationship	69%	26%	5%
Owner-contractor relationship	65%	20%	15%
Changed Condition Clauses	55%	10%	35%
Contract Price	74%	21%	5%

3. Do you believe such a concept would increase or decrease responsibilities of the following groups in the tunneling industry?

	Increase	No Effect	Decrease
Owner's responsibility	59%	27%	14%
Engineer's responsibility	90%	–	10%
Geologist's responsibility	81%	14%	5%
Contractor's responsibility	18%	23%	59%

4. It is probable that in the future, advanced techniques in instrumentation or geologic investigations will enable us to get an accurate model of the actual rock loads imposed on a support system. Any support prediction model, to be useful in the future, should be adaptable to this type of data input as it is developed. Do you believe the proposed Rock Structure Rating concept as proposed is adaptable to such change?

Yes 93% No 7%

5. Additional comments on part IV. Acceptability of Proposed Rock Structure Rating

(See Appendix A)

(See Section 4.3)

Name

form of criteria or standards which could be used. Some of the individuals were already familiar with the purpose of the research effort, others were not. To better explain the concept and the purpose of the questionnaire, additional individual reports were enclosed which included the following:

1. Paper presented at the Chicago Rapid Excavation and Tunneling Conference - June 1972 (Ref. 2)
2. Tables showing the RSR parameters and support requirement charts taken from Sections 2 and 4 respectively of Reference 1.
3. Example use of the RSR concept to determine support requirements for a hypothetical tunnel - Section 6 of Reference 1.

These reports, along with an explanatory cover letter and the questionnaire, were sent to 30 individuals, each of whom are prominent in their respective field of interest. This was followed by various discussions and correspondence so as to answer or explain questions raised by the candidates.

4.3 INDUSTRY RESPONSE

Overall response from the industry was considered excellent. Of the 30 questionnaires sent out, 25 were returned with most of the questions answered. A listing by general disciplines is given below; names of respondents are given on pages 4-12 and 4-13.

Discipline	No. of Responses
Geologist - Owner	4
Geologist - Consultant	3
Engineer - Owner	5
Engineer - Consultant	4
Contractor	3
R & D and Educational	6
	25

RESPONDENTS TO RSR QUESTIONNAIRE

Mr. Amil Dubnie - Dr. D.F. Coates
Dept. of Energy, Mines & Resources
Ottawa, Ontario, Canada

Mr. T. M. Noskiewicz
Hatch Associates, Ltd.
Toronto, Ontario, Canada

Mr. E. H. Shea, Jr.
J. F. Shea Co., Inc.
Dublin, California

Mr. A. G. Bennet
John Connell - Mott Hey &
Anerson, Hatch, Jacobs
Melbourne, Australia

U. S. Bureau of Mines
Spokane Mining Research Center
Spokane, Washington

Dr. Charles S. Robinson
Charles S. Robinson & Assoc., Inc.
Denver, Colorado

Mr. Paul G. De Marco
Grow Tunneling Corp.
New York, N. Y.

Mr. Robert S. Mayo
Robert S. Mayo & Associates
Lancaster, Pa.

Mr. Clark E. McHuron
Consulting Engineer Geologist
Santa Rosa, Ca.

Mr. Carl G. Bock
Bechtel Associates
Washington, D.C.

Mr. F. T. Lee
U. S. Geological Survey
Denver, Colorado

U. S. Bureau of Reclamation
Federal Center
Denver, Colorado

Mr. Eugene F. Casey
New York City Transit Auth.
Brooklyn, New York

Mr. Harry Sutcliffe
Bechtel Corp.
San Francisco, Ca.

Mr. Reginald Darrow
Parsons, Brinckerhoff, Tudor,
Bechtel
Oakland, Ca.

Mr. Alan L. O'Neill
U. S. Corps of Engineers
San Francisco, Ca.

Dr. Edward J. Cording
University of Illinois
Urbana, Ill.

Mr. Richard V. Proctor
Metropolitan Water District
Los Angeles, Ca.

Dr. Ernest E. Wahlstrom
Colorado School of Mines
Boulder, Colorado

Mr. John A. Trantina
Woodward - Clyde & Assoc.
San Francisco, Ca.

Mr. John W. Woodward
Pacific Gas & Electric Co.
San Francisco, Ca.

Mr. Samuel Taradash
Comm. Shearing & Stamping Co.
Youngstown, Ohio

Mr. L. B. Underwood
U.S. Corps of Engineers
Omaha, Nebraska

Dr. Madan M. Singh
ITT Research Institute
Chicago, Ill.

Mr. John F. Johnston
MacLean Grove & Co.
New York, New York

Mr. J. N. de la Vergne
J. S. Redpath Ltd.,
North Bay, Ontario

Dr. Paul LeComte
Geology and Soil Mechanics Div.
Hydro-Quebec
Montreal, P. Q.

The authors again wish to express their appreciation to those who took the time and effort to help in this research.

In addition to the above, continuing inquiries and comments regarding the RSR concept were received from both local and foreign sources. In one instance a member of the study team made a presentation on the use of the RSR method for an engineering class at a local university. Included in Handbook on Tunneling - Other engineering class - etc.

Several of the candidates expressed concern over the difficulty of trying to isolate or consider a specific factor involved in ground support determinations without first evaluating all factors which might in one way or another affect the particular tunneling situation. The reasoning being that no two tunnels present identical conditions. Another problem occurred where several individuals within the same organization were either unable to agree on a specific answer or were concerned over the possibility that a particular answer might be taken out of context and considered as a policy statement of the organization. This relates principally to potential legal aspects of contracting. Such concern was anticipated and fully appreciated by the study

team. Such reasoning may be why a prediction model has not been advanced in the past. It does, however, point out the necessity for developing some common solution which would provide realistic answers and be acceptable to all involved in tunnel construction. For the present, and at least the immediate future, it must be accepted that the prediction of ground support requirements is not an exact science and should not be construed as such for purposes of circumventing contract requirements. Also, a method of 'exact' dimensioning for support members has a relatively minor effect on total cost and effort when considering the overall tunneling process.

Most of the submitted questions could be answered by 'yes' or 'no'; ranking in order of preference; or assignment by weighted percentages on a scale of 100. Industry response to these questions is shown on the included questionnaire. The indicated answers or values reflect a straight numerical average of responses given for the particular questions. The geologic factor grouping and percentages shown for question II-2, page 4-6, is an exception to the above and is discussed later.

Responses to the six comment questions (I-3, I-9, II-4, III-2, III-8, and IV-5) covered a wide range of individual thought and suggestions. Several separate written critiques were returned which discussed the overall concept and gave suggestions for changes and/or additions, which might be made. A brief synopsis of some of the comments as well as ideas expressed during informal discussions of the RSR method are given below. Additional comments are given as Appendix A of this report.

- Fairly useful technique -
- A significant step in right direction -
- Not workable in present form -
- Should be expanded to include extreme conditions -
- Avoid using descriptions that lack dimensions -
- Highly desirable for correlation between predictions and actual rock loads monitored -
- Legal implications and effect on changed condition clauses -
- Need in situ testing to see if support is adequate -
- Misuse of basic geologic terms or concepts -
- Requires more emphasis on accurate mapping -
- Must prove reliable on first try -
- Quality and quantity of input of prime importance -
- Need explicit dimensions rather than verbal terminology -
- Require consideration of past and present tectonic stress -
- Consideration of stand-up time of excavated rock -
- Don't throw out the baby with the dirty water -
- Must consider special problems of gas and water -
- Excellent classification system for design -
- Just don't believe it will work -
- Projection of surface geology to grade most difficult -

- Factors other than geology affect type and amount of support -
- Would be a way of testing to increase confidence in instrumental data.

As seen by the above, and Appendix A, the prediction of ground support requirements is not only a subject of wide-open discussion, but one which would be of special benefit to the industry if properly developed for effective use.

4.4 EVALUATION OF INDUSTRY RESPONSE

The following discussion evaluates industry's response to the RSR prediction model questionnaire. It considers and incorporates those comments, factors, and suggestions directly related to or affecting the proposed model and which most nearly reflect different requirements as expressed by various disciplines involved in tunnel construction. The evaluation is not intended to imply or infer the endorsement or rejection by any individual or organization but rather it is presented as an objective endeavour to provide a workable and useful tool for the benefit of the industry.

Answers to 'yes - no' and preference type questions appear to reflect general industry concurrence with respect to most of the requirements and objectives of the proposed prediction model.

The importance and heavy reliance on pre-bid geology in making preditions of ground support is shown by answers to question I-1. Question I-4 indicates several types of pre-bid gelogical information which would be

most meaningful in this respect. These answers, which could be anticipated, probably reflect one or both of the following: 1) Continuation of a well indoctrinated industry procedure, or 2) lack of, or reluctancy to accept, new methods or procedures measuring rock properties in predicting ground support. Although past tunneling experience and judgement rank second as to most frequently used criteria in predicting supports, their combined weighting (33%) is somewhat less than given for pre-bid geology (41%). In a general sense this might indicate that the owner, who usually provides pre-bid geological information, should depict and include in the contract documents a fairly specific delineation of the anticipated ground support requirement. Criterion used in developing the RSR concept are essentially the same as listed by the industry as being most important.

Question I-7 emphasizes the need for improving techniques used in making geological investigations for tunnel projects. Although remote sensing or other techniques might be developed, indications are that such devices will not be available for use in the immediate or near future. Empirical relationships, as ranked second, have been derived and used in correlating RSR evaluations and support requirements for the proposed prediction model.

Question III - 3 shows the average relative values assigned to the three basic Parameters - A) General Area Geology; B) Joint Pattern and Direction of Drive; and C) Ground Water and Joint Condition. These questionnaire averages are substantially the same as used in the original RSR model as shown below:

EVALUATION OF RSR PARAMETERS

Parameters	Original Value	Industry Response (Aver.)
A	30	31
B	50	45
C	20	24

Several comments were also made to the effect that the range of rock types shown for Parameter A should be expanded to include badly broken or decomposed rock.

Most candidates had expressed a preference, whenever possible, to use quantitative or dimensional values in describing geological factors, in Question II-3, as opposed to verbal descriptions. Various suggestions were made in this respect, one of which is shown by the following table submitted by E. H. Skinner - USBM, Spokane, for mechanical properties of rock material.

DESIGN RECOMMENDATIONS

Parameter A – Rock Strength Max. Value 30

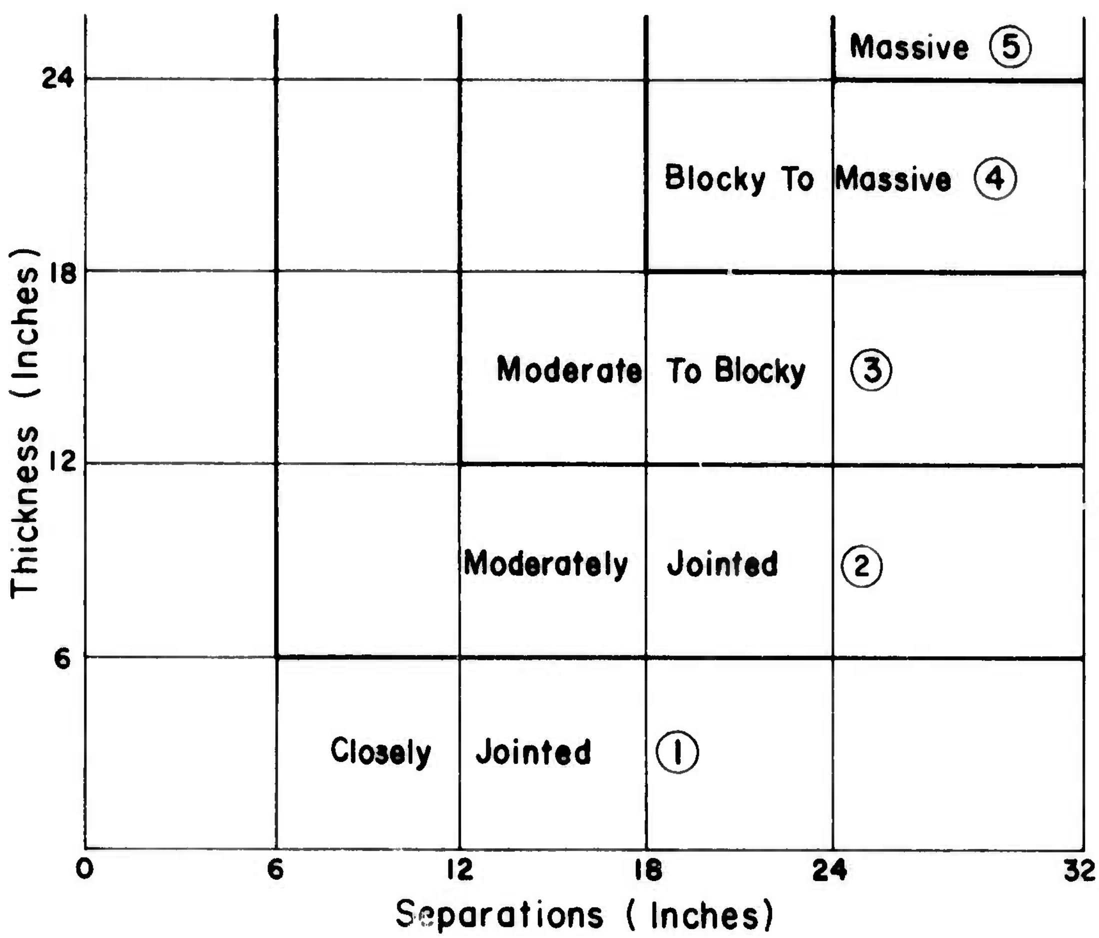
Rock Classification	LABORATORY ① UNIAXIAL COMPRESSIVE STRENGTH (psi)	FIELD ② SEISMIC VELOCITY (fps)	DESIGN ELASTIC MODULUS (psi x 10^6)
Hard Rock	< 20,000	< 15,000	5 ⟶ 9
Medium Rock	10 – 20,000	10,000 - 15,000	3 ⟶ 5
Soft Rock	5 – 10,000	5000 - 10,000	1 ⟶ 3
Decomposed Rock	>1000	>5000 ③	>1.0

1.) In-situ elastic modulus may be estimated with laboratory uniaxial elastic modulus. Divide laboratory elastic modulus by joints per foot. Joints per foot by field count only.

2.) Prediction estimates of elastic modulus may be obtained from seismic velocity and rock hardness.

3.) Assumed water saturated; if not velocity slightly greater.

Another example, regarding definitions of geological properties, relates to Parameter B which considers the anticipated joint pattern of the rock structure. Normal usage of terms such as "closely jointed" or "blocky" have different meaning to different individuals even though qualified by a numerical value. Adequately defining this factor is important in any determination of ground support requirements and was frequently referred to in the industry response. It is felt that a method proposed by Mr. John Trantina - Woodward Clyde & Associates, offers a resonable solution to this problem. It basically gives a two dimensional definition of the joint pattern as shown by the graph.



These and other comments regarding the definition of geologic factors are considered and used in formulating the final prediction model in Section 5 of this report.

Opinions expressed for questions I-5 and I-8 bear on the overall possibility or necessity of developing a ground support prediction model. Question I-5 -- whether or not present-day techniques of making geologic investigations are adequate -- is crucial, since the validity of a prediction model depends on the reliability and interpretation of developed geologic data. Although the overall consensus shows about an even distribution of thought it is interesting to note that most geologists and R & D personnel were of the opinion that present methods were not adquate, while contractors and engineering consultants felt that they were. This difference is probably due to requirements and degree of detail which each discipline thinks is essential to the problem. There is no question as to the desirability of having and using as much geological information as possible (question I-2) but it is felt that reasonable predictions can be made from findings and results obtained by the use of present-day techniques. Question I-8, reasons for installing support -- gives another insight to the problem. Most disciplines polled feel that more than 50% of all tunnel supports are installed for reasons other than on the simple basis of actual load carrying capacity or ground supporting requirements. Contractors were an exception. Reasons for installing supports as a precaution against "potential safety hazards" are more or less indeterminate, depending entirely on the personal judge-

ment of those in charge of the heading. Usually, such decisions are made immediately after the rock is exposed, allowing little time for an analysis as to the actual structural need for the support member. Undoubtedly, subsequent inspection or testing would show some of this support as being superfluous with respect to actual load carrying requirements, hence the contention of "over-supported". Convincing a walking boss that this consideration is more important than measures taken which might possibly prevent a fatal accident would be very difficult indeed.

In a broad sense, the above raises the question as to the merit or effectiveness of trying to obtain complete geological data necessary for, or attempting to make a theoretically correct support design. This does not condone "over-supporting" of tunnels as such, but rather is intended to point out the possibility and need for a reasonable compromise between technical design and real-world tunneling practices.

Whether or not surface geology should be projected to grade and anticipated supports indicated in project documents, (questions I-6 and I-7) is a problem to be resolved in the preparation of all tunnel contracts. Although industry response is generally in favor of such inclusions, it is seldom that this type of information is provided. This is probably due more to legal aspects of responsibility for changed conditions that it is to engineering or geological considerations. The continued, and perhaps increasing number of claims relating to changed conditions indicate that the more-or-less non-committal approach used in many contracts is not solving or

improving the situation. Although the area of contractural requirements is beyond the scope of this study, it is suggested that a commonly accepted method of evaluating support requirements by all the tunneling industry, both during the pre-bid and construction periods, will eventually lead to more equitable and realistic procedures to be followed in the preparation of specifications for tunnel construction and in payment for actual work performed.

Answers to questions III-5 and III-6 indicate that most candidates (90%) think that it is possible to identify physical features or conditions of a rock structure by some type of numerical scale and that an empirical relationship between geologic factors and support requirements can be established. Although these two questions were not specific as to what the numerical scale or empirical relationship should be, it appears that the basic principals used in developing the RSR prediction model are reasonable. The concept lists commonly referred to factors or groups of factors and assigns a weighted value to each with respect to its effect on the overall support requirement. Their values are subsequently correlated with support needs on the basis of an empirical relationship derived from case studies (Section 2). Question II-1 requested the candidates to rank on a scale of 100% those geologic factors which they felt were most important in this respect. The percentages shown in the questionnaire (page 4-5, 4-6) reflect numerical averages of 22 responses to this question. The following tabulation shows averages as given by the four different disciplines.

Discipline	RT	JO	RF	RP	JP	GS	JS	WF	WA	other
				Factor *						
Geologist	11	5	19	4	28	4	7	11	9	2
Engineers	10	13	11	9	18	11	8	10	10	
Contractors	15	12	8	7	20	10	12	5	8	3
R & D	17	15	12	10	15	5	8	8	6	3
Average	13	11	12	7	21	8	9	9	8	2

* See questionnaire, question II-1.

The above tabulation, as well as individual answers show wide variation in thinking as to the relative importance of the listed factors. This, of course, is also reflected in Question II-2 -- grouping of geologic factors and assignment of weighted values with respect to relative effect on the support requirement. In this latter instance, some 51 different groupings were given. Group RP + RT was listed 7 times; JO + JP, -- 5 times; WF + WA, -- 4 times, and WF + JS, -- 3 times. Thirteen groupings were listed twice, the remainder only once. The percentages shown for Question II-2 are averages given by 12 respondents who included the indicated groupings in their evaluation. Regardless of the individual differences, there appears to be the general consensus that the most important consideration in the evaluation or prediction of support requirements deals with the anticipated joint pattern of the rock structure. Rock types and rock properties appear to be next, followed by some consideration as to the effect of water in-flow, and condition of the joint surface. This ranking of the

combined relative effect on the overall support requirement for various geologic factors is in general agreement with values assigned to Parameters A, B and C as used in the RSR concept. These two questions (II-1 and II-2) are fundamental and as anticipated the most difficult to answer and evaluate. They involve consideration of 1) what is meant by each of the listed geologic factors, 2) whether or not they can be or should be treated individually or collectively and 3) what if any is their effect on the support requirement. Indeed, this concern was expressed by several respondents who commented that some geologic factors were undistinguishable from others or were ambiguous in meaning. Although clarifying or establishing acceptable standards and limits of measure for these factors is a major task to be accomplished in finalizing the prediction model, industry response to the questionnaire, and findings of this and previous research efforts indicate that the range of potential answers is being narrowed to within acceptable limits of agreement. This is inferred somewhat by answers to questions III-1; whether or not most essential geologic factors have been included in the RSR concept and III-4; whether or not weighted values assigned to Parameter A, B and C reasonably reflect differences in support requirements. Both were affirmative.

Any prediction model must be adaptable to such modifications as may be determined by continued research or use; opinions expressed for question IV-4 indicate that this is possible with the RSR concept.

Potential benefit of an accepted method for predicting ground support

is shown by answers to questions IV-1, 2 and 3. Most candidates think there would be a general improvement in relationship between various disciplines and in other aspects pertaining to tunneling.

The evaluation of multiple opinions and comments is difficult and always presents the interpretative problem as to whether or not answers given to a specific question by one discipline should be weighted more heavily than those given by another. Although this was considered, the final evaluations were based on equal consideration for all responses. Since effective use of a prediction model requires general acceptance by all disciplines it was felt that this was the best approach even though it induces or implies the requirement of compromise between some presently accepted standards or criteria.

4.5 INDUSTRY ACCEPTANCE OF PREDICTION MODEL

Based on industry's response, comments, suggestions and overall interest, it is concluded that the ground support prediction model would be acceptable and could be widely used as a practical tool in the planning and design of future civil works tunnels. It is similarly concluded that to a large extent, initial RSR use will probably be in the area of comparing or verifying ground support systems as determined by other methods. This more-or-less cautious approach is understandable and is essentially the same approach used in developing the model wherein some 53 case histories were considered. With a basic model format to follow, requirements, findings and results of future work can; when appropriate, be effectively inte-

grated so as to increase the degree of confidence in making predictions of ground support requirements.

Various adjustments and revisions expressed by industry are incorporated in the proposed prediction model as discussed in Section 5. Additional refinements which may be indicated by results of continued use can readily be made. In all cases, and as previously mentioned, the effective use of a ground support prediction model requires engineering judgment and compromise from each discipline. A cooperative approach should prove beneficial to all concerned.

Use of a prediction model by the mining industry would probably be limited to determination of support required for access or haulage tunnels Although these tunnels are usually small in cross section, their aggregate length could, in some cases, constitute a major undertaking in which a reasonable prediction of ground support would be of substantial benefit. There may be other instances, but in general, it is assumed that the acceptance and use of a prediction model by the mining industry would be somewhat less than in civil applications. This is due in part to inherent differences in requirements, procedures and objectives between the two industries. On the other hand, geologic and in situ testing data developed in typical mining operations could be of significant value in ultimate refinement and acceptance of the prediction model by the tunnel industry, if properly correlated with model parameters and goals.

SECTION 5

GROUND SUPPORT PREDICTION MODEL

5.1 INTRODUCTION

The basic concept used in developing the initial ground support prediction model was discussed in Section 1. In brief, it provides a method of rating a rock structure with respect to its need for support during tunneling operations. This rating is indicated on a numerical scale which relates to most rock tunneling situations. It is determined by considering and evaluating various geological and construction parameters which are applicable to the tunneling operations and which are available for consideration in the pre-construction period. The higher ratings indicating good rock conditions wherein little or no support would be required, lower ratings indicating various degrees of support requirements. Using data from case studies and developed empirical relationships, steel rib support (size and spacing) that would be required for a particular size of tunnel has been determined and correlated with the RSR values. The concept has been expanded to include consideration of shotcrete and rock bolt type of support.

The object of this research phase is to further develop and verify the prediction model for practical usage to mining and/or civil applications. Two of the indicated requirements were 1) Incorporate additional case history data so as to refine and develop the concept and 2) seek industry evaluation and acceptance of the concept. These two areas of effort were discussed in Sections 2, 3, and 4.

This section of the report incorporates findings, comments, data and recommendations as developed or determined in the previous sections with respect to the initial RSR prediction model. The overall methodology and empirical relationships used in finalizing the model are similar to those described in Section 1 and Reference 1. Since case history data and empirical relationships are interdependent (any singular change or adjustment of a weighted parameter value or limit of measure necessitates re-evaluation of all case study data) it was necessary to make a "trial run" for each potential adjustment. Results and calculations pertaining to those intermediate steps are not included herein except as they affect the final ground support prediction model.

5.2 MODEL FORMAT & CONCEPT

Critical review of the original RSR format by the tunnel industry indicated that specific changes or modifications should be made. They relate primarily to the weighted numerical values assigned to Parameters A, B, and C, and to methods or measures used to define various factors. The revised format is shown as Figure 5.1. Comparison with Figure 1.1 shows adjustment and changes that have been made.

Industry also indicated the desirability of extending the scope of the model so as to include a larger range of rock conditions. To a certain extent this has been accomplished by expanding the basic rock type descriptors and respective weighted values shown for Parameter A. (See paragraph 5.5) However, the model is still not applicable to soft squeezing or swell-

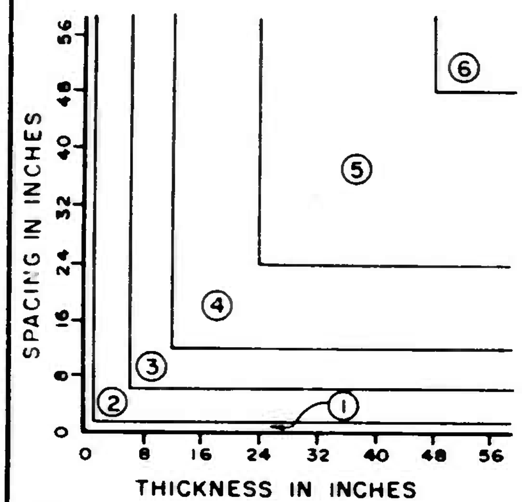
ROCK STRUCTURE RATING
PARAMETER "A"
GENERAL AREA GEOLOGY

MAX. VALUE 30

BASIC ROCK TYPE				
	HARD	MED.	SOFT	DECOMP.
IGNEOUS	1	2	3	4
METAMORPHIC	1	2	3	4
SEDIMENTARY	2	3	4	4

	GEOLOGICAL STRUCTURE			
	MASSIVE	SLIGHTLY FAULTED OR FOLDED	MODERATELY FAULTED OR FOLDED	INTENSELY FAULTED OR FOLDED
TYPE 1	30	22	15	9
TYPE 2	27	20	13	8
TYPE 3	24	18	12	7
TYPE 4	19	15	10	6

Figure 5.1



ROCK STRUCTURE RATING
PARAMETER "B"
JOINT PATTERN
DIRECTION OF DRIVE

MAX. VALUE 45

	STRIKE ⊥ TO AXIS					STRIKE ∥ TO AXIS		
	DIRECTION OF DRIVE					DIRECTION OF DRIVE		
	BOTH	WITH DIP		AGAINST DIP		BOTH		
	DIP OF PROMINENT JOINTS					DIP OF PROMINENT JOINTS		
	FLAT	DIPPING	VERTICAL	DIPPING	VERTICAL	FLAT	DIPPING	VERTICAL
1 VERY CLOSELY JOINTED	9	11	13	10	12	9	9	7
2 CLOSELY JOINTED	13	16	19	15	17	14	14	11
3 MODERATELY JOINTED	23	24	28	19	22	23	23	19
4 MODERATE TO BLOCKY	30	32	36	25	28	30	28	24
5 BLOCKY TO MASSIVE	36	38	40	33	35	36	34	28
6 MASSIVE	40	43	45	37	40	40	38	34

NOTES: Flat 0 - 20°; Dipping 20° - 50°; Vertical 50° - 90°

Figure 5.1 (continued)

ROCK STRUCTURE RATING
PARAMETER "C"
GROUND WATER
JOINT CONDITION

MAX. VALUE 25

ANTICIPATED WATER INFLOW (GPM/1000')	SUM OF PARAMETERS A + B					
	13 - 44			45 - 75		
	JOINT CONDITION					
	GOOD	FAIR	POOR	GOOD	FAIR	POOR
NONE	22	18	12	25	22	18
SLIGHT (<200 gpm)	19	15	9	23	19	14
MODERATE (200-1000 gpm)	15	11	7	21	16	12
HEAVY (>1000 gpm)	10	8	6	18	14	10

Joint Condition: Good = Tight or Cemented; Fair = Slightly Weathered or Altered; Poor = Severely Weathered, Altered, or Open

Figure 5.1 (continued)

ing ground conditions where support requirements would likely be determined by use of criteria developed from soil mechanics or other analytical analyses dealing with soil pressures and loads, all of which is beyond the scope of the present research effort.

Another mentioned extension of the model; and one which should be of substantial benefit to the tunneling industry, would be to show a correlation between RSR values and a "drillability factor" as it relates to potential use of a boring machine for tunnel excavation. Although not considered in the present study, it is felt that such a correlation could be made within the same general format and procedures used in developing the prediction model. Since "drillability" relates to both mechanical properties of the rock (hardness, abrasiveness, compressive strength, etc.) and to the anticipated joint pattern or fracture system, it is possible that a reasonable evaluation of the applicability of a boring machine could be made by expanding the definitions and/or limits of measure presently used for the three basic RSR parameters. It would require a separate correlation between RSR values and some common datum or measure of assessing the drillability of the rock structure. This would probably be an empirical relationship similar to the rib ratio used to define support requirements.

Based on industry's response and other comments and evaluations, the overall concept of describing properties of a rock structure by means of a numerical scale and using correlations based on empirical relationships appears to be a reasonable approach to the problem. The model is structured to accommodate more exacting data or information that may be developed.

It encompasses geologic and construction factors normally considered and provides a common basis for predicting ground support requirements for future tunnels.

5.3 RIB RATIO

As mentioned in paragraph 1.4, the correlation between RSR values and actual ground support was obtained by use of a "rib-ratio" (RR) which gives a relation between steel rib support used in a tunnel study section and a theoretical rib support determined for a common datum condition. The determination of the rib-ratio is shown on page 5-8. Figure 5.2 shows the spacing of common sizes of steel ribs for various tunnel diameters as calculated for the datum condition. The RR for a particular tunnel study section is obtained by dividing the rib spacing listed on Figure 5.2 by the actual rib spacing used in the study section and multiplying by 100. Assuming the study section to be a 14 ft circular tunnel supported by 6H20 steel ribs on 5 ft centers then the RR is 46 (2.32 ÷ 5.0 x 100). Rib ratios were determined for each tunnel study section and subsequently used to develop the empirical relationship between determined RSR values and ground support requirements which is discussed in the following paragraphs.

5.4 CASE HISTORY DATA

All case history projects were initially considered, and respective RSR values determined, on the basis of original model format (Figure 1.1). Due to subsequent revisions and other modifications (Figure 5.1) it was necessary to re-evaluate all tunnel study sections so as to obtain new RSR

DETERMINATION OF RIB RATIO

Terzaghi Empirical Formula for Maximum Roof Load for Loose, Cohesionless Sand Below Water Table (From Ref.No. 8) Page 70, Table 2:

$$P1 = [1.38 \quad (B + H \quad)] \times B \times \gamma_t \qquad (1)$$

Where: P1 = Vertical load on rib (lb. per linear foot of tunnel)

B = Tunnel width (ft.)

H_t = Tunnel height (ft.)

γt = Unit weight of sand (assumed 120 lb./cu.ft.)

Formula (1) applies to tunnels with a semi-circular arch.

$$P_1 = 1.38 \; (B + H_t) \; \times \; B \times 120$$

$$P_1 = 165.6 \; B \; (B + H_t) \qquad (2)$$

For tunnels that are circular or where height (Ht) = width (B) = Dia. (D)

$$P_1 = 165.6 \; D \; (D + D)$$

$$P_1 = 165.6 \times 2D^2$$

$$P_1 = 331 \; D^2 \qquad (3)$$

Using load table from "Rock Tunneling With Steel Supports" by Proctor and White, Page 238: (Reference No. 3)

Pt = Pr x D Where Pt = Total allowable load on rib (lb.)

Pr = Chart value of allowable load per foot of tunnel width (lb.)

To find theoretical rib spacing (Sd) for "Datum" Condition:

$$Sd = \frac{Pt}{P1}$$

$$Sd = \frac{Pr \times D}{331 \; D^2}$$

$$Sd = \frac{Pr}{331 \; D} \qquad (4)$$

The rib ratio is a measure of the actual tunnel support provided compared to the datum and is expressed as:

$$RR = \frac{Sd}{Sa} \times 100 \qquad (5)$$

Where Sa is actual spacing (ft.) of ribs used in sample tunnel.

THEORETICAL SPACING (Sd) OF TYPICAL RIB SIZES FOR DATUM CONDITION SPACING GIVEN IN FEET

	TUNNEL DIAMETER										
Rib Size	10'	12'	14'	16'	18'	20'	22'	24'	26'	28'	30'
4I7.7	1.16										
4H13.0	2.01	1.51	1.16	0.92							
6H15.5	3.19	2.37	1.81	1.42	1.14						
6H20		3.02	2.32	1.82	1.46	1.20					
6H25			2.86	2.25	1.81	1.48	1.23	1.04			
8WF31				3.24	2.61	2.14	1.78	1.51	1.29	1.11	
8WF40					3.37	2.76	2.30	1.95	1.67	1.44	1.25
8WF48						3.34	2.78	2.35	2.01	1.74	1.51
10WF49								2.59	2.22	1.91	1.67
12WF53										2.19	1.91
12WF65											2.35

Figure 5.2

values. Actual support installations and calculated rib ratios (see paragraph 5.3) were, of course, not affected. Figure 5.3 lists the 53 projects and sample tunnel sections which were investigated in conjunction with development of the prediction model. Rock type and individual values for parameters A, B and C are as determined by use of Figures 5.1. Where applicable, a TBM factor is shown in accordance with discussion on page 1-16. The table also shows actual support and calculated RR for each tunnel section.

Figure 5.4 is a graph of points plotted with respect to RSR values and rib ratios determined for some 190 sample tunnel sections. The graph shows an empirical relationship between RSR and RR developed by the same general procedures as discussed in Section 1 and Reference 1. Twenty points, which fell well above the curve envelope were eliminated from consideration. They indicated either an extremely conservative support system (over-supported) or a loading condition, such as squeezing rock beyond the scope of the prediction model. Although sample tunnel sections which were unsupported (RR = 0) help define the limit of RSR values wherein no support is required, they do not contribute to, and are not included in the calculation of the empirical relationship curve. There is usually a "grey" area in differentiating between an unsupported tunnel section and one which requires only nominal support. In actual practice nominally supported sections normally occur at the beginning or end of a supported section of tunnel, and are usually evidenced by use of scattered rock bolts or other minimal "umbrella" type of support. This support situation is shown by the deviation from the plotted curve on Figure 5.4 and reflects an evalua-

ROCK STRUCTURE RATINGS AND RIB RATIOS DETERMINED FOR CASE STUDY TUNNELS											
CASE NO.	TUNNEL SIZE (Ft.)	ROCK TYPE	RSR DETERMINATION					SUPPORT		
			A	B	C	TBM FACTOR	TOTAL	SIZE	SPACE	RIB RATIO
1-1	24x24 HS	1	22	38	19	-	79	-	-	0
-2		2	13	24	9	-	46	8W28	4.0'	34
2-1	12x12 HS	1	15	11	18	-	44	5W18.9	5.0'	50
3-1	22 Dia.	2	13	11	11	-	35	8H34	4.0'	48
-2		2	13	15	15	-	43	8H34	4.0'	48
-3		2	13	23	11	-	47	8H34	5.5'	35
-4		2	13	11	9	-	33	8H34	4.0'	48
4-1	22 Dia.	2	13	19	12	-	44	8H34	5.0'	39
-2		2	9	15	9	-	33	8H34	4.0'	48
-3		3	13	15	12	-	40	8H34	5.0'	39
5-1	9x9 HS	4	10	15	9	-	34	4H13	4.0'	60
-2		4	10	15	12	-	37	4H13	5.0'	48
-3		4	10	13	12	-	35	4H13	4.8'	50
-4		4	10	17	9	-	36	4H13	4.7'	51
-5		4	10	12	12	-	34	4H13	4.5'	53
-6		4	10	12	7	-	29	5H18.9+	2.3'	183
-7		4	6	9	9	-	24	4H13+	2.5'	96
-8		3	12	14	9	-	35	4H13	5.0'	48
-9		3	12	23	9	-	44	4H13	5.0'	48
-10		3	12	14	6	-	32	4H13	4.0'	60
-11		3	12	23	6	-	41	4H13+	6.0'	40
-12		3	12	23	12	-	47	4H13	6.0'	40
6-1	20x20 HS	1	15	22	19	-	56	8M32.6	4.0'	57
-2		1	15	17	15	-	47	8H40+	2.7'	94
-3		2	13	17	15	-	45	8H40+	2.0'	127
-4		2	13	17	15	-	45	8M32.6+	2.4'	103
-5		2	8	17	9	-	34	8M32.6	2.8'	83
-6		2	8	17	9	-	34	8M32.6+	2.3'	107
-7		2	8	17	15	-	40	8M32.6	4.1'	54
-8		2	8	17	9	-	34	8M32.6	4.1'	54
7-1	14x14 HS	1	30	40	18	-	88	-	-	0
-2		1	30	40	21	-	91	-	-	0
-3		1	30	40	21	-	91	-	-	0
-4		1	30	40	23	-	93	-	-	0
-5		1	30	40	21	-	91	-	-	0
-6		1	30	40	23	-	93	-	-	0
-7		1	22	35	14	-	71	-	-	0
-8		1	22	35	18	-	75	-	-	0

Figure 5.3

ROCK STRUCTURE RATINGS AND RIB RATIOS DETERMINED FOR CASE STUDY TUNNELS										
CASE NO.	TUNNEL SIZE (Ft.)	ROCK TYPE	RSR DETERMINATION					SUPPORT		
			A	B	C	TBM FACTOR	TOTAL	SIZE	SPACE	RIB RATIO
8-1	13x13 HS	4	10	13	12	-	35	6H20	4.0'	65
-2	13 Dia.	3	12	16	9	1.18	44	6B16	3.0'	70
9-1	14 Dia.	3	18	22	9	1.18	58	6I12.5	6.4'	21
-2		3	18	22	9	1.18	58	3/4 RB	3'x5'	19
10-1	20 Dia.	3	18	29	19	1.17	77	-	-	0
-2		3	18	29	19	1.17	77	4I7.7	4.5'	8
11-1	19x19 HS	3	18	22	19	-	59	1"RB	6x6	11
-2		3	18	22	19	-	59	6W20	5.6'	20
12-1	11x11 HS	4	10	13	18	-	41	4W13	3.0'	58
13-2	11x11 HS	4	10	13	18	-	41	4W13	3.0'	58
17-1	20x20 HS	2	13	7	7	-	27	8W31	3.0'	71
-2		1	15	11	15	-	41	6W25	3.4'	43
-3		1	15	14	15	-	44	6W25	4.0'	37
18-1	8 Dia.	3	13	14	18	-	45	4W13	6.0'	47
19-1	8 Dia.	3	13	14	12	-	39	4W13	6.0'	47
20-1	34 Dia.	3	12	23	18	-	53	10W49	4.5'	27
-2		3	12	24	18	-	54	10W49	4.5'	27
21-1	22x30 HS	2	13	19	22	-	54	8W28	6.7'	19
-2		2	13	25	19	-	57	8W28+	5.7'	23
-3		2	13	25	15	-	53	8W28+	5.6	23
-4		2	13	25	19	-	57	8W35	6.0'	28
-5		2	13	25	22	-	60	8W35	6.0'	28
22-1	24H. Dia.	3	12	14	12	-	38	10W33	3.2'	53
-2	33H. Dia.	3	12	14	12	-	38	10W45	2.6'	54
23-1	18.5 HS	2	13	28	15	-	56	6M25	5.9'	29
-2		4	10	7	9	-	26	8M40	4.0'	78
-3		2	13	19	15	-	47	6M25	4.4'	39
-4		2	13	28	7	-	48	6M25	5.5'	31
-5		2	13	16	9	-	38	6M25+	4.2'	40
-6		2	13	22	7	-	42	6M25	5.0'	34
-7		2	13	17	11	-	41	6M25	4.0'	43
-8		4	10	15	9	-	34	8M32.6+	4.3'	51

Figure 5.3 (continued)

ROCK STRUCTURE RATINGS AND RIB RATIOS
DETERMINED FOR CASE STUDY TUNNELS

CASE NO.	TUNNEL SIZE (Ft.)	ROCK TYPE	RSR DETERMINATION					SUPPORT		
			A	B	C	TBM FACTOR	TOTAL	SIZE	SPACE	RIB RATIO
24-1	18.5 HS	4	10	16	12	-	38	6M25	4.0'	43
-2		2	13	17	18	-	48	6M25	5.2'	33
-3		3	12	22	15	-	49	6M25	5.9'	29
-4		2	20	22	11	-	53	6M25	6.1'	28
-5		4	10	17	12	-	39	6M25	4.0'	43
25-1	23x22 HS	3	18	14	18	-	50	10x10Tim.	2.5'	29
-2		1	22	14	22	-	58	10x10Tim.	5.9'	13
-3		1	15	14	18	-	47	10x10Tim.	2.9'	43
-4		4	6	10	9	-	25	16x16Tim.	2.5'	85
-5		1	15	14	11	-	40	12x12+	2.7'	40
-6		3	12	14	7	-	33	12x12+	2.5'	53
-7		1	22	14	18	-	54	10x10+	4.3'	18
26-1	23x23 HS	2	18	22	22	-	62	8W24+	6.1'	18
-2		2	18	22	25	-	65	8W24+	6.5'	17
-3		2	13	22	18	-	53	8W24+	4.0'	28
-4		2	20	22	22	-	62	8W24+	6.1'	18
-5		2	20	22	22	-	62	8W24+	6.3'	18
-6		2	13	22	12	-	47	8W24+	3.1'	48
-7		2	20	22	12	-	54	8W24+	6.2'	18
-8		2	13	14	18	-	45	8W24	2.3'	55
27-1	14x15 HS	1	22	29	25	-	76	-	-	0
-2		1	22	29	25	-	76	-	-	0
-3		1	22	29	23	-	74	-	-	0
-4		2	20	39	25	-	84	-	-	0
-5		1	22	28	25	-	75	-	-	0
-6		2	20	24	25	-	69	-	-	0
-7		2	12	11	12	-	35	6M20	3.8'	61
28-1	18x18 HS	1	22	40	23	-	85	-	-	0
-2		1	22	40	22	-	84	-	-	0
-3		1	22	36	22	-	80	-	-	0
-4		1	22	36	22	-	80	-	-	0
-5		1	22	28	22	-	72	-	-	0
-6		1	22	36	19	-	77	-	-	0
-7		4	15	22	12	-	49	6H25	5.0'	36
29-1	14x14 HS	1	22	34	25	-	81	-	-	0
-2		4	15	22	15	-	52	6H20	5.5'	42
-3		4	15	10	12	-	37	6H20	4.5'	52
30-1	19x19 HS	2	20	34	22	-	76	-	-	0
-2		2	13	24	12	-	49	6H25	4.0'	41

Figure 5.3 (continued)

ROCK STRUCTURE RATINGS AND RIB RATIOS DETERMINED FOR CASE STUDY TUNNELS										
CASE NO.	TUNNEL SIZE (Ft.)	ROCK TYPE	RSR DETERMINATION					SUPPORT		
			A	B	C	TBM FACTOR	TOTAL	SIZE	SPACE	RIB RATIO
31-1	17x16 HS	3	12	14	11	-	37	10x10+	2.5'	56
-2		4	6	14	9	-	29	12x12+	2.1'	78
-3		4	10	14	9	-	33	10x10+	2.3'	60
-4		4	6	14	7	-	27	12x12+	2.3'	80
32-1	17x16 HS	3	12	14	12	-	38	10x10+	2.9'	45
-2		4	10	22	12	-	44	10x10	3.4'	38
-3		4	6	14	7	-	27	12x12+	2.1'	106
-4		4	6	14	11	-	31	12x12	2.0'	101
33-1	22x30 HS	2	20	22	15	-	57	RB+	4'x4'	14
-2		2	20	22	10	-	52	6H20+	4.4'	25
-3		2	13	24	8	-	45	8H34+	3.9'	37
-4		2	13	23	12	-	48	6H20+	4.3'	30
-5		2	20	23	15	-	58	6H20+	4.7'	22
-6		2	18	19	15	-	47	6H20+	4.6'	25
-7		2	20	23	15	-	58	6H20+	4.9'	15
34-1	21x21 HS	3	12	19	15	-	46	8W40	4.0'	63
-2		3	7	13	7	-	27	8W40	2.0'	126
-3		3	12	17	9	-	38	8W40	2.1'	119
-4		3	12	17	15	-	44	8W40	2.6'	97
-5		3	12	22	18	-	52	8W37	3.8'	62
-6		3	12	22	15	-	49	8W37	3.6'	64
-7		3	7	22	18	-	47	8W37	2.9'	82
-8		3	12	20	15	-	47	8W37	4.0'	59
-9		3	12	15	15	-	42	8W37	3.8'	61
35-1	23x23 HS	2	20	35	25	-	80	-	-	0
-2		2	13	28	18	-	59	8W20+	5.8'	18
-3		2	20	28	15	-	63	8W18+	6.3'	16
-4		2	13	14	18	-	45	8W24+	3.1'	43
-5		2	13	28	15	-	56	8W20+	6.2'	17
36-1	16 Dia.	3	18	17	15	1.20	60	Shotcrete	3.5"TH.	59
-2		3	18	17	9	1.20	53	Shotcrete	3.5"TH.	59
37-1	17x17 HS	3	18	19	18	-	55	4W13+	4.7'	21
-2		3	18	24	18	-	60	4W13+	5.8'	14
-3		3	18	11	12	-	41	6W20+	3.9'	33
-4		2	20	28	22	-	70	4W13	5.1'	16
-5		3	12	11	18	-	41	4W13+	2.1'	40
38-1	17x17 HS	3	12	32	12	-	56	4W13+	3.7'	22

Figure 5.3 (continued)

ROCK STRUCTURE RATINGS AND RIB RATIOS DETERMINED FOR CASE STUDY TUNNELS										
CASE NO.	TUNNEL SIZE (Ft.)	ROCK TYPE	RSR DETERMINATION					SUPPORT		
			A	B	C	TBM FACTOR	TOTAL	SIZE	SPACE	RIB RATIO
38-2	17x17 HS	3	12	25	7	-	44	4W16+	3.4'	33
-3		2	20	24	19	-	63	4W13+	8.5'	10
-4		3	12	23	9	-	44	4W16+	4.0'	26
-5		2	13	24	19	-	56	4W13+	4.8'	18
-6		2	13	25	15	-	53	6W20+	4.0'	36
-7		2	13	30	15	-	58	4W13	5.8'	14
-8		3	12	22	11	-	45	4W13+	3.1'	29
-9		3	12	28	18	-	58	4W13+	4.0'	21
39-1	23 Dia.	1	22	24	19	-	65	8I18.4	5.5'	16
-2		1	22	16	15	-	53	8I18.4	4.0'	23
-3		1	22	37	23	-	82	-	-	0
-4		2	20	16	12	-	48	8I18.4	3.6'	28
40-1	32x32 HS	3	18	35	23	-	76	1" RB	3.5x3.5	18
-2		3	18	22	14	-	54	8W34.3	3.9'	24
-3		1	22	35	23	-	80	1" RB	3.5x3.5	18
41-1	20x20 HS	1	22	28	19	-	69	1" RB	4x5	18
-2		3	18	24	15	-	57	1" RB	4x5	18
42-1	16 Dia.	3	18	23	18	-	59	1" RB	5x5	18
43-1	18 Dia.	4	15	30	22	-	67	6W15.5	4.0'	28
-2		4	15	23	18	-	56	6W15.5	4.0'	28
44-1	17 Dia.	3	12	23	15	-	50	7I15.3	5.0'	25
45-1	10x10 HS	2	12	19	9	-	40	4W13	4.0'	50
46-1	11 Dia.	3	18	42	18	-	78	3/4" RB	4.5x4.5	18
47-1	21x21 HS	2	13	22	19	-	54	8W17	3.0'	35
-2		2	13	28	15	-	56	8W17	3.0'	35
48-1	22 Dia.	3	12	23	18	-	53	8I25.5	3.0'	39
49-1	26 Dia.	3	18	22	18	-	58	8W24	4.0'	25
-2		3	18	22	18	-	58	10W33	4.0'	23
50-1	24x24 HS	1	22	22	15	-	59	1" RB	5x5	13
51-1	27x27 HS	3	18	35	22	-	75	1" RB	5x5	11
-2	18 Dia.	3	18	29	22	-	69	1" RB	4x5	20

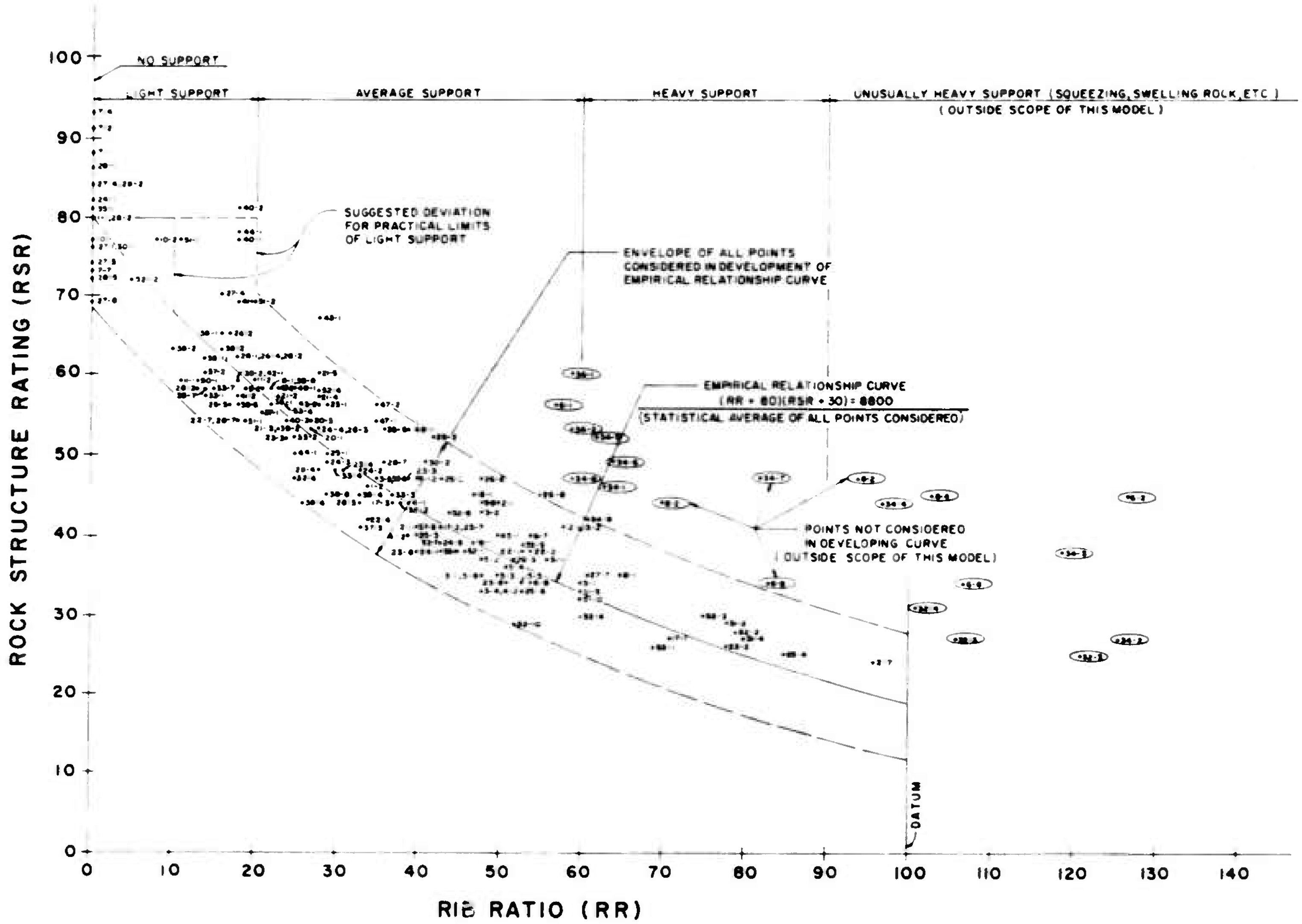
Notes: 8 W 28+ indicates size most prevalent in this area of tunnel (more than one size used)

Figure 5.3 (continued)

ROCK STRUCTURE RATINGS AND RIB RATIOS DETERMINED FOR CASE STUDY TUNNELS											
CASE NO.	TUNNEL SIZE (Ft.)	ROCK TYPE	RSR DETERMINATION					SUPPORT		
			A	B	C	TBM FACTOR	TOTAL	SIZE	SPACE	RIB RATIO
52-1	12x12 HS	3	7	23	8	-	38	6 H 20+	6.5'	46
-2		3	7	14	7	-	28	6 H 20+	3.8'	79
-3		2	8	11	6	-	25	6 H 20+	2.5'	121
-4		2	8	16	6	-	30	6 H 20+	5.0'	60
-5		2	13	17	9	-	39	6 H 20+	5.6'	53
-6		2	13	19	15	-	47	6 H 20+	8.6'	35
-7		2	13	17	9	-	39	6 H 20+	6.9'	43
-8		2	13	19	11	-	43	6 H 20+	6.8'	44
-9		1	15	28	15	-	58	6 H 20+	10.8'	28
-10		2	13	24	15	-	52	6 H 20+	10.3'	29
-11		1	15	28	19	-	62	6 H 20+	some	14
-12		2	13	36	23	-	72	6 H 20+	some	5
53-1	15x15 HS	2	8	11	7	-	26	4 H 13	1.5'	69
-2		4	10	11	9	-	30	Shotcrete	4" Th.	75
-3		3	18	19	15	-	52	1" R.B.	4'x5'	24
-4		1	22	19	15	-	56	1" R.B.	4'x5'	24

Notes: 8 W 28+ indicates size most prevalent in this area of tunnel (more than one size used)

Figure 5.3 (continued)



Final Correlation of RSR and RR

Figure 5.4

tion of low rib ratios (less than 20) wherein actual support was minimal as compared to the datum condition or where support may have been placed primarily as a safety precaution. The descriptive support designations (light, medium, heavy, and very heavy) shown at the top of the graph are given merely to show possible correlation between the prediction model and other methods used to describe ground support requirements.

Industry comments indicated some concern over the use of case history data in developing the RSR concept, the contention being that if sample sections were in fact "over-supported" the model would perpetuate the same condition. In a general sense all tunnels that have not collapsed due to structural failure of a support system could be classed as "over-supported." Until such time that exact determination of rock loads and conditions can be predicted, it must be accepted that tunnel support will continue toward the conservative. In most cases the difference in cost and effort occasioned by the use of a heavier rib or closer spacing than might be dictated by a theoretical correct design, would probably be insignificant in comparison to differences resulting from initial misinterpretation or prediction as to whether or not any support would be required. The prediction model attempts to identify those rock structures which would normally require support during tunnel construction and indicates appropriate support systems to be used. Based on findings and results of this research effort, it is concluded that case history data (excluding the 20 sample points as noted above) does provide a realistic appraisal of the ground support requirement. No prediction model including mathematical or theoretical analysis will

eliminate the judgment factor for those in charge of the heading as to what constitutes a safe, adequately supported tunnel section during construction. The goal should be to provide a means of making realistic appraisals of support requirements during the pre-construction period which can be readily used and correlated with encountered conditions so as to augment or facilitate the instant heading determination of an adequate support system.

5.5 EMPIRICAL RELATIONSHIP RSR - ROCK LOADS

A correlation between RSR and RR values was shown by the empirical equation developed for the average curve on Figures 5.4. That equation considers some 140 sample points contained within the relatively narrow envelope shown on the graph.

Basic Equation: $(RR + 80)\ (RSR + 30) = 8800$

RSR values and Rib Ratios:

RSR	19	25	30	35	40	45	50	55	60	65	70	75	80
RR	100	80	67	55	46	37	30	24	18	13	8	4	0

As seen by the above tabulation, the upper (80) and lower (19) limits of RSR values, as defined by rib ratios of 0 and 100 respectively, have been extended to include a larger range or type of rock structures. (see page 1-13) Since RR basically defines an anticipated rock load (datum condition) by considering the load carrying capacity of different sizes of steel ribs, it follows that RSR values can also be expressed in terms of unit rock loads for various sized tunnels. Derivation of this empirical relationship follows on page 5-20 and 5-21. A correlation of RSR values and rock loads as

EMPIRICAL EQUATIONS FOR RSR, RR AND ROCK LOAD

Using values of rock structure rating (RSR) and rib ratios (RR) computed from case study geologic sections, a graph (Figure 5,4) was plotted using RSR from 0 to 100 as ordinate and RR from 0 to 100 as abscissa, equation (6) shows the average curve for these points. See page 5-8 for definitions.

$$(RR + 80)\ (RSR + 30) = 8800 \tag{6}$$

Or

$$RSR = \left[\frac{8800}{RR + 80}\right] - 30 \tag{7}$$

It was observed that a direct relationship exists for the rock structure rating and unit rock load (Wr = K/Sq. Ft.) for a specified size of tunnel. This empirical relationship can be derived as follows:

$$Wr = \frac{Pr}{Sa} \div 1000 \tag{8}$$

$$Sa = \frac{Pr}{1000 \times Wr} \tag{9}$$

Combining equation (5) from page 5-8 and (7)

$$RSR = \left[\frac{8800}{\left(\frac{Sd \times 100}{Sa}\right) + 80}\right] - 30 \tag{10}$$

Substituting for Sa (equation (9))

$$RSR = \left[\frac{8800}{\left(\frac{Sd \times 100 \times Wr \times 1000}{Pr}\right) + 80}\right] - 30 \tag{11}$$

Restating equation (4) from page 5-8

$$\frac{Sd}{Pr} = \frac{1}{331D} \tag{12}$$

Substituting for $\frac{Sd}{Pr}$ in equation (11)

$$RSR = \left[\frac{8800}{\left(\frac{100,000\ Wr}{331D}\right) + 80}\right] - 30 \tag{13}$$

Or

$$RSR = \left[\frac{8800}{\left(\frac{302\ Wr}{D}\right) + 80}\right] - 30 \tag{14}$$

Restated to find Wr, given RSR & D:

$$Wr = \frac{D}{302}\left[\left(\frac{8800}{RSR + 30}\right) - 80\right] \tag{15}$$

Or

$$Wr = \frac{D \times RR}{302} \tag{16}$$

General empirical equation for (6), (14) & (15) can be written as follows:

$$(RR + A)\ (RSR + B) = C \tag{6}$$

$$RSR = \left[\frac{C}{\left(\frac{302\ Wr}{D}\right) + A}\right] - B \tag{14}$$

$$Wr = \frac{D}{302}\left[\left(\frac{C}{RSR + B}\right) - A\right] \tag{15}$$

For this report:

$A = 80$

$B = 30$

$C = 8800$

determined by use of equation (14) page 5-21 is shown by Figure 5.5. Once an RSR value has been determined for a particular tunnel section it is possible, by use of Figure 5.5, to indicate anticipated rock loads which must be supported. For instance, if an RSR value of 40 has been determined for a 20 ft. tunnel, the anticipated rock load is about 3 kips per sq. ft. It is noted that the same RSR value denotes different rock loads depending on size of tunnel.

This correlation between RSR values and anticipated rock loads can be used to determine appropriate tunnel support systems based on the type or quality of the rock structure predicted to be penetrated by the tunnel. Since most case history data pertain to steel ribs, this correlation relates primarily to rib support. However, the determined rock loads can be used (see paragraph 5.6) to indicate a pattern of rock bolts or thickness of shotcrete which would provide adequate support for the predicted type of rock structure.

5.6 GROUND SUPPORT REQUIREMENTS

Three primary support systems are considered: 1) steel ribs, 2) rock bolts and 3) shotcrete, any one or combinations of which could be used for many varied rock conditions and tunnel sizes. The most appropriate system would normally be determined on the basis of cost analysis made for each with respect to other tunneling subsystems. A brief discussion and evaluation of various new concepts of ground support is given in Appendix B.

CORRELATION OF ROCK STRUCTURE RATING TO ROCK LOAD AND TUNNEL DIAMETER

(Based on Formula (14) in Figure 4.5)

TUNNEL DIAMETER (D)	(Wr) ROCK LOAD ON TUNNEL ARCH (K/sq.ft.)											
	0.5	1.0	1.5	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
	CORRESPONDING VALUES OF ROCK STRUCTURE RATINGS (RSR)											
10'	62.5	49.9	40.2	32.7	21.6	13.8						
12'	65.0	53.7	44.7	37.5	26.6	18.7						
14'	66.9	56.6	48.3	41.4	30.8	22.9	16.8					
16'	68.3	59.0	51.2	44.7	34.4	26.6	20.4	15.5				
18'	69.5	61.0	53.7	47.6	37.6	29.9	23.8	18.8				
20'	70.4	62.5	55.7	49.9	40.2	32.7	26.6	21.6	17.4			
22'	71.3	63.9	57.5	51.9	42.7	35.3	29.3	24.3	20.1	16.4		
24'	72.0	65.0	59.0	53.7	44.7	37.5	31.5	26.6	22.3	18.7		
26'	72.6	66.1	60.3	55.3	46.7	39.6	33.8	28.8	24.6	20.9	17.7	
28'	73.0	66.9	61.5	56.6	48.3	41.4	35.7	30.8	26.6	22.9	19.7	16.8
30'	73.4	67.7	62.4	57.8	49.8	43.1	37.4	32.6	28.4	24.7	21.5	18.6

Figure 5.5

Support capabilities or requirements for a particular size of steel rib are usually expressed by the rib spacing as determined for anticipated rock load and tunnel size. Determination of rib spacing for the datum condition was discussed in paragraph 5.3. Results were shown on Figure 5.2. They reflect a rib ratio of 100 and a corresponding RSR value of 19 (see paragraph 5.5) Rib spacing for other RSR values or equivalent rock loads vary proportionately from the datum spacing as the inverse ratio of the respective rib ratios. Using this relationship, it is possible to show typical spacing for various rib sizes required for different tunnel sizes and RSR values as given on Figure 5.6. After determining the RSR value for a particular rock structure the size and spacing of steel ribs which would satisfy the support requirement of various sized tunnels can be identified.

General appraisals of rock bolt (spacing or pattern) and shotcrete (thickness) support with respect to anticipated rock loads were made in the previous research study (Reference 1). Data obtained from additional case studies performed under this contract was not sufficient in quantity or detail to disprove the previous assumptions. Although there is increased use of these types of support, it is likely that it will be several years before historical data would be meaningful. Research sponsored by Governmental Agencies and similar efforts being put forth by the tunnel industry should provide, in the not too far future, more definitive criterior for the design and use of rock bolts and shotcrete for tunnel support. For the present, however, and since rock bolt and shotcrete data available from case studies showed fairly reasonable correlation with the prediction model, the initial

RIB SPACING (IN FEET) BASED ON RSR AND TUNNEL DIAMETER

RR	RSR	10' DIAMETER			12' DIAMETER		
		4I7.7	4H13	6H15.5	4H13	6H15.5	6H20
100	19	1.16	2.01	3.19	1.51	2.37	3.02
80	25	1.45	2.51	3.99	1.89	2.96	3.78
67	30	1.73	3.00	4.76	2.25	3.54	4.51
55	35	2.11	3.65	5.80	2.75	4.31	5.49
46	40	2.52	4.37	6.93	3.28	5.15	6.57
37	45	3.14	5.43	8.62	4.08	6.41	8.16
30	50	3.87	6.70		5.03	7.90	
24	55	4.83	8.38		6.29		
18	60	6.44			8.39		
13	65	8.92					

RR	RSR	14' DIAMETER			16' DIAMETER		
		4H13	6H15.5	6H25	6H15.5	6H25	8W31
100	19	1.16	1.81	2.86	1.42	2.25	3.24
80	25	1.45	2.26	3.58	1.78	2.81	4.05
67	30	1.73	2.70	4.27	2.12	3.36	4.84
55	35	2.11	3.29	5.20	2.58	4.09	5.89
46	40	2.52	3.93	6.22	3.09	4.89	7.04
37	45	3.14	4.89	7.73	3.84	6.08	8.76
30	50	3.87	6.03	9.53	4.73	7.50	
24	55	4.83	7.54		5.92	9.38	
18	60	6.44	10.05		7.89		
13	65	8.92			10.92		

RR	RSR	18' DIAMETER			20' DIAMETER		
		6H15.5	6H25	8W40	6H20	8W31	8W48
100	19	1.14	1.81	3.37	1.20	2.14	3.34
80	25	1.42	2.26	4.21	1.50	2.68	4.18
67	30	1.70	2.70	5.03	1.79	3.19	4.99
55	35	2.07	3.29	6.13	2.18	3.89	6.07
46	40	2.47	3.93	7.33	2.61	4.65	7.26
37	45	3.08	4.89	9.11	3.24	5.78	9.03
30	50	3.80	6.03		4.00	7.13	
24	55	4.75	7.54		5.00	8.91	
18	60	6.33	10.05		6.67		
13	65	8.77			9.23		

Figure 5.6

RIB SPACING (IN FEET) BASED ON RSR AND TUNNEL DIAMETER

RR	RSR	22' DIAMETER			24' DIAMETER		
		6H25	8W31	8W48	6H25	8W40	10W49
100	19	1.23	1.78	2.78	1.04	1.95	2.59
80	25	1.54	2.23	3.48	1.30	2.44	3.24
67	30	1.84	2.66	4.15	1.55	2.91	3.87
55	35	2.23	3.24	5.05	1.89	3.55	4.71
46	40	2.67	3.87	6.04	2.26	4.24	5.63
37	45	3.32	4.81	7.51	2.81	5.27	7.00
30	50	4.10	5.93	9.27	3.46	6.50	8.63
24	55	5.13	7.42		4.33	8.13	
18	60	6.83	9.89		5.78		
13	65	9.46			8.00		

RR	RSR	26' DIAMETER			28' DIAMETER		
		8W31	8W40	10W49	8W31	8W48	12W53
100	19	1.29	1.67	2.22	1.11	1.74	2.19
80	25	1.61	2.09	2.78	1.39	2.18	2.74
67	30	1.93	2.49	3.31	1.66	2.60	3.27
55	35	2.35	3.04	4.04	2.02	3.16	3.98
46	40	2.80	3.63	4.83	2.41	3.78	4.76
37	45	3.49	4.51	6.00	3.00	4.70	5.92
30	50	4.30	5.57	7.40	3.70	5.80	7.30
24	55	5.38	6.96	9.25	4.63	7.25	9.13
18	60	7.17	9.28		6.17	9.67	
13	65	9.92			8.54		

RR	RSR	30' DIAMETER		
		8W40	10W49	12W65
100	19	1.25	1.67	2.35
80	25	1.56	2.09	2.94
67	30	1.87	2.49	3.51
55	35	2.27	3.04	4.27
46	40	2.72	3.63	5.11
37	45	3.38	4.51	6.35
30	50	4.17	5.57	7.83
24	55	5.21	6.96	9.79
18	60	6.94	9.28	
13	65	9.62		

Figure 5.6 (continued)

appraisals and relationships are used.

Rock bolts are considered on the basis of a simple correlation between both strength (working stress) and rock loads as shown below:

$$\text{Spacing or pattern of bolts in feet (s)} = \sqrt{\frac{Bs}{Wr}}$$

Where Bs is the allowable tensile strength of the bolt expressed in kips per sq. in. and Wr is the rock load in kips per sq. ft.

For the purposes of this study and assuming allowable working stress of 30,000 lb. per sq. in., the required pattern for different size bolts can be shown as:

$$S\ (5/8''\ \varnothing\ \text{bolts}) = \sqrt{\frac{9.2}{Wr}}$$

$$S\ (3/4''\ \varnothing\ \text{bolts}) = \sqrt{\frac{13.5}{Wr}}$$

$$S\ (1''\ \varnothing\ \text{bolts}) = \sqrt{\frac{24}{Wr}}$$

$$S\ (1\text{-}1/4\ \varnothing\ \text{bolts}) = \sqrt{\frac{37.5}{Wr}}$$

In all cases, appropriate bolt length, required torque, and adequate anchorage are assumed.

The suggested empirical relationship between shotcrete requirements (nominal thickness in inches) and predicted rock loads is:

$$\text{Nominal thickness } t = 1'' + \frac{Wr}{1.25}$$

This relationship, as in the case of rock bolts, appears to be conservative for the cases investigated.

It is realized that the above rock bolt and shotcrete correlations are very general in nature and do not allow for certain inherent structural advantages or properties associated with each. For instance, a principal advantage of shotcrete is its ability to inhibit or restrict initial loosening of the exposed rock arch. Individual blocks react as a compression ring when properly bolted. Although consideration as to the effect of these characteristics on the support requirements should, if possible, be included in the model it is doubtful that they would affect significantly the initial prediction of tunnel support. Exceptions would be in determining supports for large underground caverns or other areas where time is available for in situ testing and other investigations.

The developed relationship between RSR values, rock loads and support systems are used to show typical ground support which would be required for various tunnel sizes and rock conditions. This is shown by the "Support Requirement Charts" for 10, 14, 20, 24 and 30 foot diameter tunnels of Figure 5.7. Similar charts could be prepared for other tunnel diameters or for horse shoe shaped tunnels when considering applicable widths as being roughly equivalent to a given diameter. When considering flat arch sections it would be necessary to calculate rock loads (Wr) based on RSR and applicable tunnel dimensions and then design supports as noted in paragraph 6.3.

The charts would be used as follows: Assume a 30 ft. tunnel to be

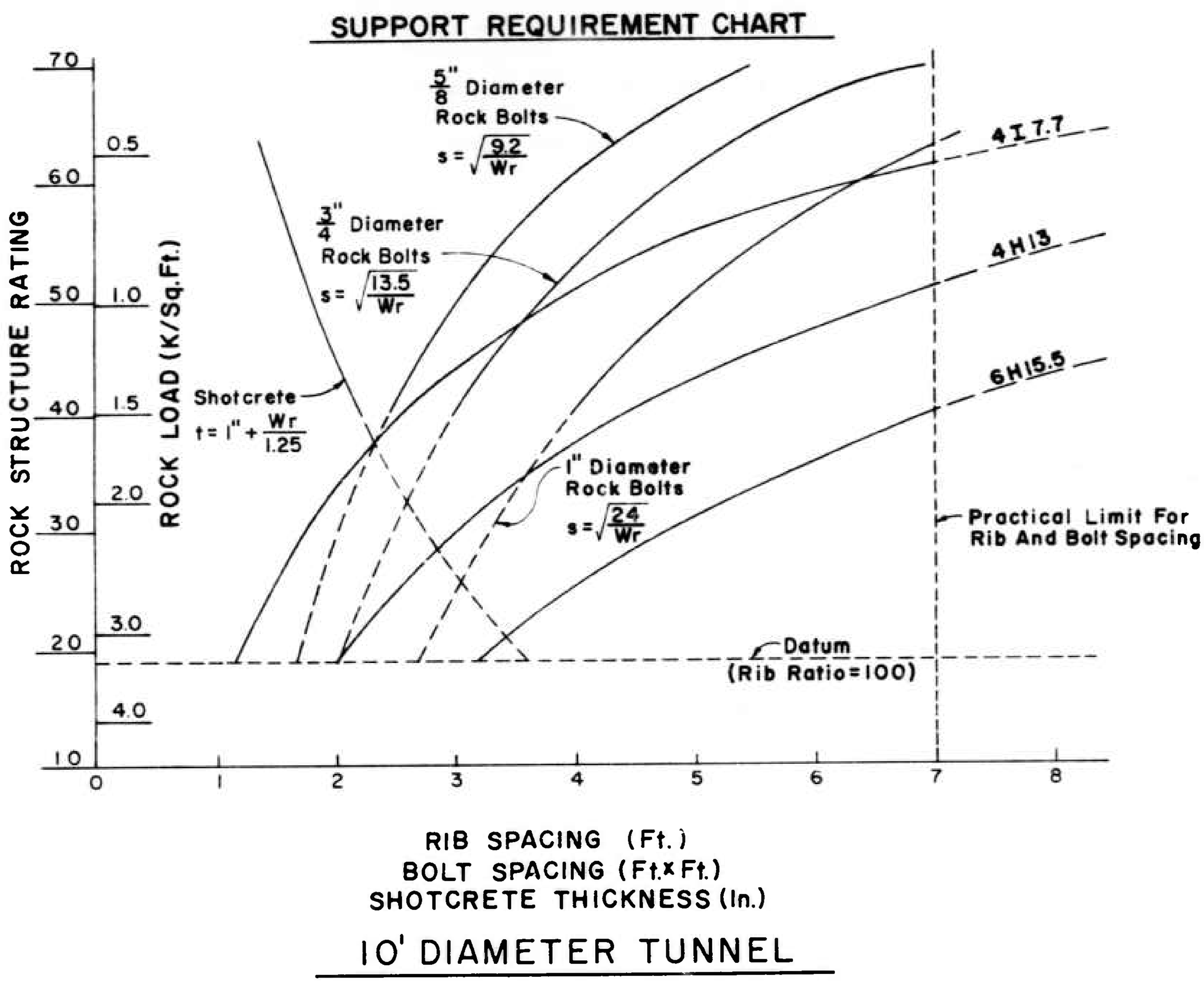
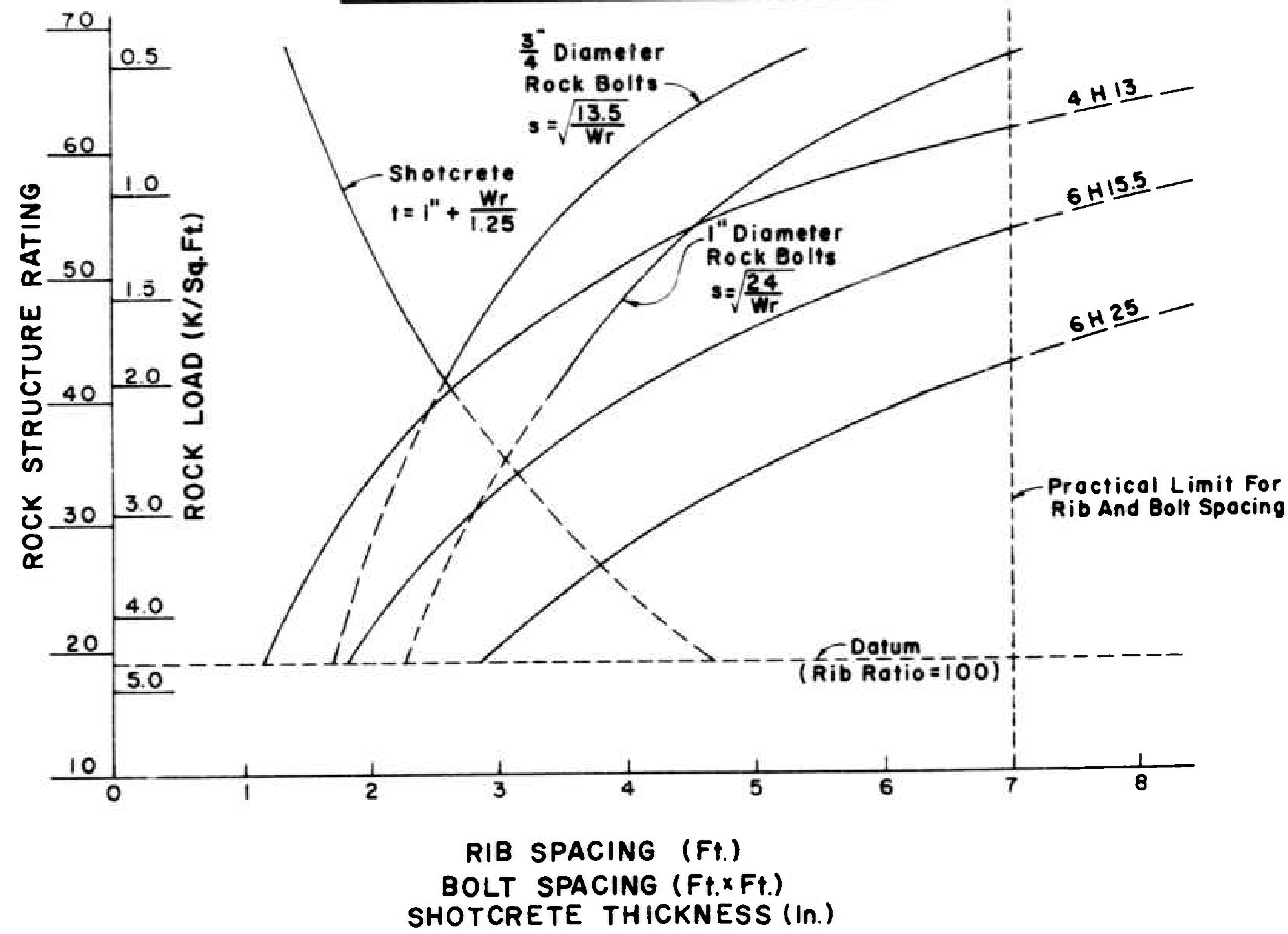

SUPPORT REQUIREMENT CHART
ROCK STRUCTURE RATING
ROCK LOAD (K/Sq.Ft.)
70
60
50
40
30
20
10
0.5
1.0
1.5
2.0
3.0
4.0
0
1
2
3
4
5
6
7
8
5" / 8 Diameter Rock Bolts
$s = \sqrt{\frac{9.2}{Wr}}$
3" / 4 Diameter Rock Bolts
$s = \sqrt{\frac{13.5}{Wr}}$
Shotcrete
$t = 1'' + \frac{Wr}{1.25}$
1" Diameter Rock Bolts
$s = \sqrt{\frac{24}{Wr}}$
4 I 7.7
4 H 13
6 H 15.5
Practical Limit For Rib And Bolt Spacing
Datum (Rib Ratio=100)
RIB SPACING (Ft.)
BOLT SPACING (Ft.x Ft.)
SHOTCRETE THICKNESS (In.)
10' DIAMETER TUNNEL

Figure 5.7

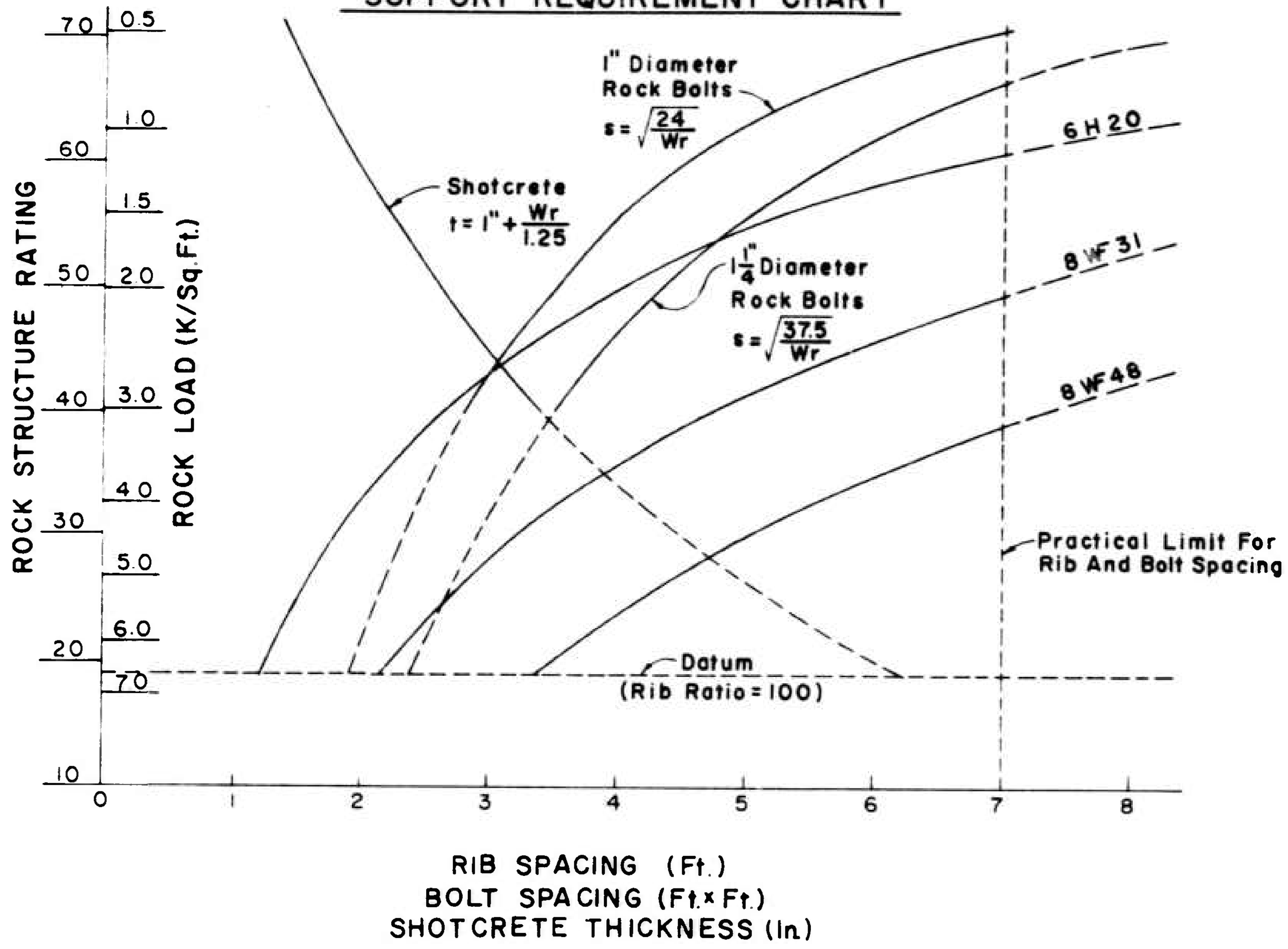
SUPPORT REQUIREMENT CHART



14' DIAMETER TUNNEL

Figure 5.7 (continued)

SUPPORT REQUIREMENT CHART



20' DIAMETER TUNNEL

Figure 5.7 (continued)

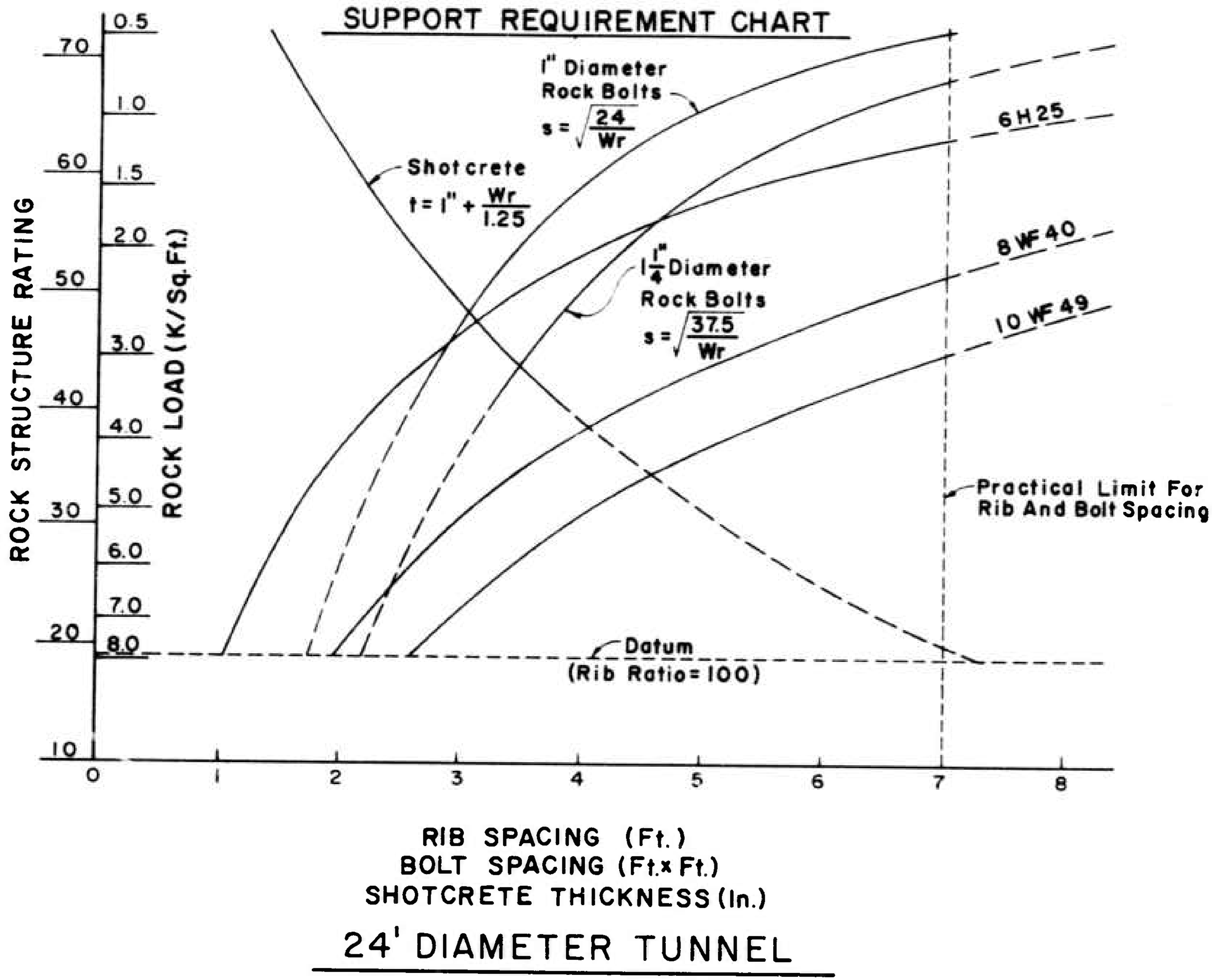
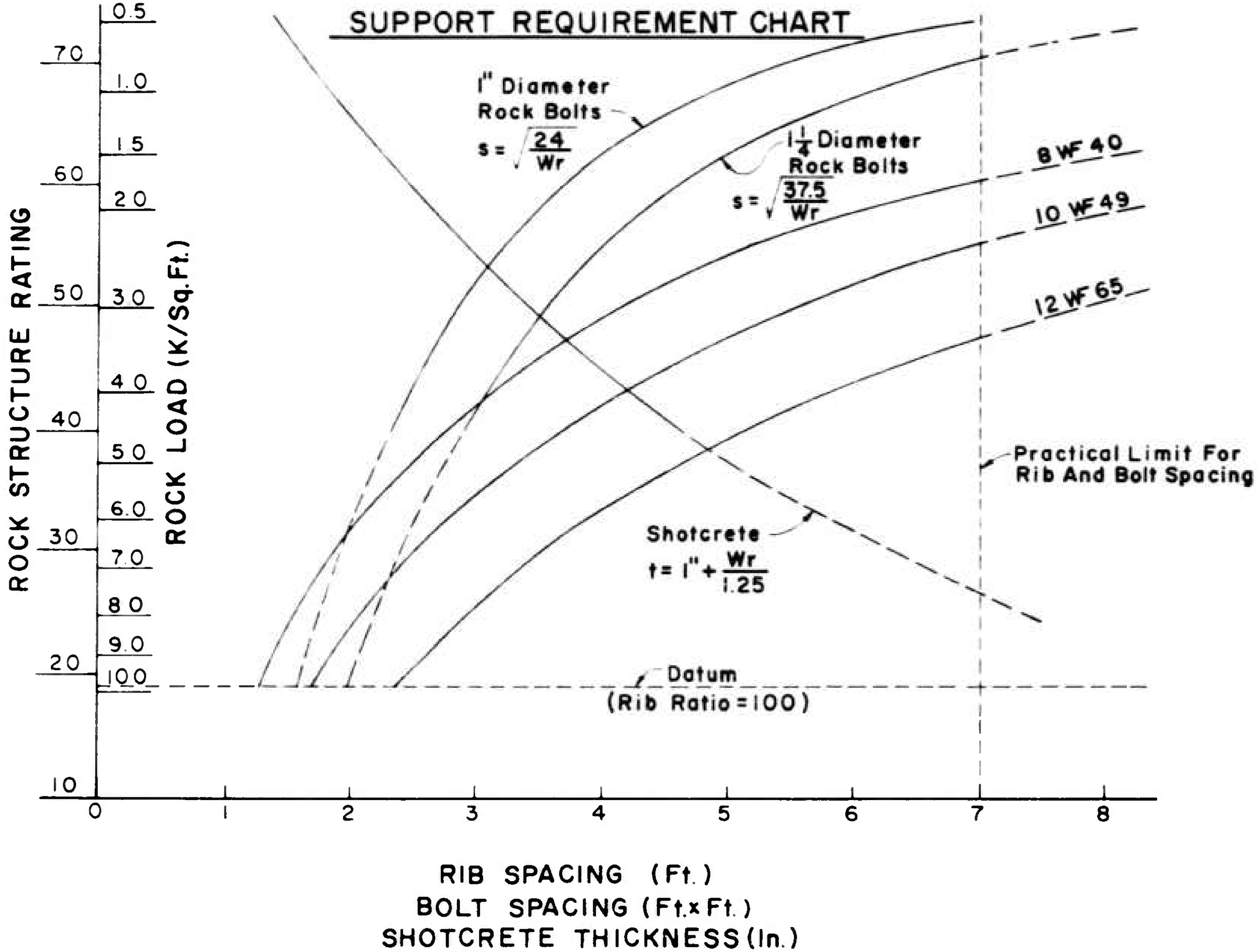


Figure 5.7 (continued)



30' DIAMETER TUNNEL

Figure 5.7 (continued)

driven through a rock structure with a predicted RSR value of 60. A horizontal line drawn to the right of RSR 60 on the 30 ft. diameter chart intersects four support system curves. Vertical lines from respective intersections to the bottom scale indicates the following requirements:

1. Shotcrete - 2-1/2" nominal thickness
2. Rock bolts 1" Ø 3.7 ft. pattern
3. Rock bolts 1-1/4" Ø 4.5 ft. pattern
4. 8WF 40 Ribs - 7 ft. ctrs.

Although each system would be evaluated with respect to the overall tunneling operation, it is likely that in this instance shotcrete would be used. Note that steel ribs are at their maximum recommended spacing for an RSR of 60 with this diameter tunnel.

RSR values less than 19, indicated by the dashed 'datum' line on the charts, reflect the need for very heavy structural support. Values in the general range of 70 - 80 indicate areas where minimal or light supports may be required (see paragraph 5.4). Tunnel sections with a predicted RSR value of 80 or greater would be unsupported.

By adjusting the predicted RSR value in accordance with discussion on page 1-19, the charts could also be used in determining support requirements for machine driven tunnels.

5.7 USE OF PREDICTION MODEL

Although the structure and format of the ground support prediction model has intentionally been kept as simple and straight forward as

possible so as to amplify and encourage its use by those involved in tunnel construction, effective use and assignment of weighted numerical values require a comprehensive understanding of both geologic and engineering requirements. Application of the RSR model to a particular project would consist of the following steps:

1) Investigation, review and evaluation of known geologic and construction data available in the pre-bid period. This information to be recorded on forms as shown on Figure 2.1. If distinct geologic sections are apparent, specific information pertaining to each would be noted.

2) Determination of respective RSR values using Figure 5.1 and applicable data from item 1 above.

3) Using a specific Support Requirement Chart for the considered tunnel size (Figure 5.7), and the determined RSR value, typical support systems are identified. Decision as to most appropriate system would require separate evaluation with respect to proposed tunneling operation. Anticipated rock loads can be read from the correlations shown on the Support Requirement Chart or obtained from Figure 5.5.

A tunnel profile would be developed showing either predicted support (type and amount) or unsupported sections along the centerline. The profile and associated RSR data would be used for planning, designing and costing of the tunnel and would also provide a common means for correlation and comparison between encountered and predicted conditions. Envisioned use of the prediction model was illustrated by considering a hypothetical tunnel project given in Appendix C.

Evaluations and determinations as noted for steps 1 and 2 above would require the combined efforts of both geologist and engineers. The specified factors and limits of measure of the model format would enable (essentially require) these disciplines to reach a common understanding as to what is meant and the relative effect on support requirement of various geologic and construction conditions. As mentioned, this will probably require certain compromises between the two, but once accomplished, there would be a standard approach or guide for support determination throughout the job. Those in the heading should be able to verify or adjust RSR values on basis of previous evaluation of geologic factors. Periodic adjustments of RSR values could be made if encountered conditions were significantly different from anticipated.

It is obvious that the RSR value is fundamental in the prediction or determination of ground support. Through continued use and familiarization with the model, factors and pre-bid evaluations, it is possible that a heading crew would soon be able to verify or adjust the predicted RSR value based on observed conditions of the rock structure.

SECTION 6

FIELD VERIFICATION EXPERIMENTS

6.1 INTRODUCTION

A stringent requirement for eventual acceptance of the prediction model as a practical working tool of the tunneling industry is aptly stated in one of the responses to the RSR questionaire - "must prove reliable on first try". Although very demanding in context it does signify a prime prerequisite of any new concept. However, the complexity and inherent unknowns involved in the prediction of sub-surface conditions are such that "instant" success is unlikely and that an acceptable degree of reliability will not be achieved until the model is adequately field tested on various tunneling situations over a period of time.

This testing of the model was initiated under the present research effort wherein several on-going projects were investigated. Ground support requirements for each were determined by use of the prediction model. As construction proceeded, actual support installations were compared with the respective predictions. Due to limited nature of current tunneling activity and corresponding time required for construction, it was difficult to find suitable projects which were being started and completed within the research period. Consequently, some of the field experiments have not been fully evaluated (comparison of predicted and actual support) at the present time.

Selection of on-going projects to be used for field application of the

of the prediction model was mutually agreed by the TPO and a member of the research team. A brief project description and comments pertaining to field investigations is given in paragraph 6.2.

6.2 FIELD EXPERIMENT PROJECTS

NEW MELONES TUNNEL: The New Melones tunnel, near Jamestown, California, is a diversion tunnel for the proposed New Melones Dam. It is 3800 feet long and was driven by drill and blast method using heading and bench. The horseshoe shap excavation is 31 feet wide and 37 feet high. Excavation was completed and the concrete lining begun when the site was visited in July 1972. In addition to inspecting the tunnel, the study team discussed the project with representatives of the Corps of Engineers and the contractor joint venture Ball-Granite. This was the largest tunnel in the United States to that time, entirely supported by shotcrete. Both the Corps and the contractor were deservedly proud of their accomplishment and were enthusiastic of the use of this support method.

The rock mass consists of layers of meta-volvanic rock interbedded with meta-sandstones, slate, slate breccia and serpentine. The bedding is almost vertical and the rock is generally blocky to massive except in narrow fault and shear zones where it is closely jointed and shattered. The entire tunnel above the invert is shotcreted. In most areas there is 4" of shotcrete in the arch and 2" on the sidewalls. In the fault and shear zones the shotcrete support has been supplemented with a few steel ribs.

CUAJONE TUNNELS: It is unfortunate that during the period of this research the number of rock tunnel projects in the United States available to the study team were very limited. To overcome this difficulty, and to extend the field studies to selected foreign and mining-type operations, it was decided to use the Cuajone Tunnels in southern Peru.

This project consists of a series of five railroad tunnels in the Departments of Moguegua and Tacna which will be used to haul copper ore concentrate from the Cuajone Copper Mine to Toquepala. The horseshoe shaped tunnels are being constructed for the Southern Peru Copper Corporation under the supervision of the Utah Construction and Mining Co. They are excavated 22' high and 24' wide by drilling and blasting full face, in rock consisting mostly of granite, granodiorite, diorite, and rhyolite porphyry. The rock is hard and generally competent except in fault zones where it is shattered and crushed.

Although it was not possible for the study team to visit the job site during the construction period, these tunnels were chosen because access to the pre-construction geology reports and current progress reports showing as-built conditions was available. In addition, one member of the study team had visited the job site prior to construction. Two of the tunnels, Cuajone Nos. 4 and 5, were being excavated during this study period; 19,200 feet of No. 4 (total 48,400 feet) is now excavated and all 7,600 feet of No. 5 .

Although geologists had spent considerable time on pre-construction

investigation, the scope of the project (88,800 feet of tunnels), the mountainous terrain, and lack of roads, limited these investigations primarily to surface geology. This data had to be projected as much as 2,000 feet vertical to tunnel grade without the aid of boring logs. The type of data needed for RSR evaluation was therefore lacking, and interpretation of verbal descriptions had to be used.

Supports for these tunnels included steel ribs, rock bolts, shotcrete, and varying combinations of each. Since possible combinations of support are limitless, an approximate comparison of these to the predicted supports is given as equivalent rib ratio (RR) values. (See paragraph 6.3)

WASHINGTON METRO SUBWAY: The largest single tunneling project now underway in the United States is the Washington Metro Subway. Portions of this project are close enough to the surface to be excavated by cut and cover methods. Of the remaining sections, some are tunneled in soft ground but most will be in rock, including several large underground stations.

Section 1A0061 of the Rockville Route was chosen for field study for several reasons. It is one of the longest sections, with over 18,000 feet of single track tunnel, a two track transition section, a crossover section and over 2,000 feet of exploratory drifts for underground stations. It was bid in December 1972 and a prediction of ground support requirements was made based on the RSR concept by the study team prior to the bid date based solely on the geologic information made available to the bidders. This prediction assumed excavation to be by drill and blast. The study team subse-

quently learned that the contractor, Morrison-Knudsen Co. plans on using a tunnel boring machine for the single track tunnels. The table of predicted support requirements shown in Figure 6.1 has been revised to include a TBM factor for these sections.

It is unfortunate that none of these tunnel sections have been excavated to date to check these support predictions. They are included so that they can be compared to actual supports by interested readers during the progress of the project. The rock in this area consists of chlorite schist, schistose gneiss, and quartz-diorite gneiss.

CARLIN CANYON TUNNELS: These twin highway tunnels each about 1,400 feet long, are being constructed for Interstate Route 80 in Elko County, Nevada by Lockheed Shipbuilding and Construction Company under the supervision of the Nevada Department of Highways. They are being excavated as heading and bench using drilling and blasting. The excavated horseshoe shaped arch is 38 feet wide and 30 feet high. When the job site was visited in May 1973, both headings were completely excavated and the contractor was removing the benches.

Although the project was begun prior to the time the study team received the pre-bid plans, specifications and geology report, the estimate of support requirements was based entirely on these documents. In preparing this estimate, the study team avoided any knowledge of the contractor's or engineer's estimate, even to ignoring the bid quantity for temporary support. The rock penetrated by the tunnel consists of closely interbedded

sedimentary rock including sandstones, siltstones, shales, limestones and conglomerates, with almost vertical bedding planes. Despite the complexity of the rock mass the geologic prediction was fairly accurate, being based on a projection of rock features from an adjacent Southern Pacific Railroad Tunnel.

The original support estimate was based on 14 W 61 steel ribs with a shotcrete alternate. This was later revised to an equivalent 8 W 67 rib to compare more easily to the supports actually used. It is interesting to note that the engineer, the contractor and the study team, each, independently estimated support required for the full length of tunnel with the study team quantity midway between the other two.

NORAD EXPANSION: In 1961 excavation was begun on the underground complex called NORAD to house the North American Air Defense Command. This complex consisted of access and ventilation tunnels, offices, fuel and water storage, generator and heating areas. This was constructed in the massive pink granite of Cheyenne Mountain, Colorado. In the late 1960's it was decided to expand this complex to include a complete power plant to make NORAD self-sustaining.

This expansion project is the sixth case study of this report. It consists of two large chambers for the power plant and cooling tower as well as various sized interconnecting tunnels for access, air intake and air exhaust. The excavation used the drill and blast method with heading and bench excavation in the larger chambers. This work was performed by the Tiro Con-

struction Company under contract to the U. S. Corps of Engineers. Excavation was complete when visited by the study team in October 1972. All areas were reinforced by rock bolt on patterns specified by the Corps of Engineers. Specified smooth wall blasting was successfully produced in the hard granite.

It is likely that basic criteria used in design of ground support for this project considered factors not normally associated with typical tunnel construction. For one the construction rock is exceptional, and the emphasis on excavation procedures and ground support exceed that in normal tunnel construction. This must be considered in the correlation of predicted and actual support as determined, in eventual verification of the prediction model.

6.3 IMPLEMENTATION OF PREDICTION MODEL

The projects were investigated in a manner similarly described in paragraph 5.7 and elsewhere in this report. Available geologic and construction data was reviewed, evaluated and recorded on study formats shown as Figure 2.1. Each project was considered as several test sections depending on applicable geology and construction requirements. RSR values were determined for each section. Using appropriate Support Requirement Charts (Figure 5.7) the types of support (steel ribs, shotcrete or rock bolts) that could be used and which would be adequate for the predicted ground conditions were identified and listed. For those tunnel sections with a relatively high RSR value and for which it would be questionable as to whether or not support would be required, the prediction is shown as applying only to a

percent of the total section length, the remainder being unsupported. This applies primarily to the Cuajone Tunnels and is noted accordingly. Actual support installations were subsequently recorded and compared with the respective predictions. Figure 6.1 is a summary tabulation. It shows individual tunnel sections considered for each project, the determined RSR values and corresponding rib ratios, the predicted support alternatives, actual support installations of the completed sections and the actual rib ratio as determined in accordance with paragraph 5.3. In cases where actual support consisted of either shotcrete or rockbolts an equivalent RR was determined by using the empirical relationships discussed in paragraph 5.6. For instance, knowing the actual thickness of shotcrete it is possible to determine anticipated rock load (Wr.) which in turn is related to an equivalent steel rib and corresponding rib ratio for the particular tunnel section. Similar evaluations were made to determine equivalent rib ratios for those sections in which actual installations consisted of a combination of support systems such as shotcrete plus steel ribs. These rib ratios (predicted and actual) are subsequently used ot evaluate results of the field experiments.

Transition sections 1 and 2a and the crossover section 7c, shown for the Washington Metro (field study 4) have flattened arches. Prediction of rib supports for these sections was based on the anticipated rock loads (Wr) as indicated by the respective RSR values and the applicable physical dimensions, using design procedures outlined in Example 2, Chapter 11 of Rock Tunneling with Steel Supports (Ref. 3). Predictions of shotcrete and rock

FIELD CASE STUDY NO. 1 - NEW MELONES TUNNEL

STUDY SECT.	PREDICTED		PREDICTED SUPPORT ALTERNATES*			ACTUAL SUPPORTS	ACTUAL (EQUIV) RR
	RSR	RR	STEEL RIBS	SHOTCRETE THICKNESS	1" ROCK BOLT PATTERN		
1	55	24	8 W 40 @ 4-1/2'	3"	3 x 3	4" Shotcrete (+ Ribs for 40')	39
2	34	58	12 W 65 @ 3-1/2'	6"	2 x 2	6" Shotcrete (+ Ribs for 35')	63
3	50	30	8 W 40 @ 4'	4"	2-1/2x2-1/2	4" Shotcrete (+ Ribs for 55')	37
4	39	48	10 W 49 @ 3'	5"	2 x 2	2" Shotcrete & 8 W 40 @ 5'	37
5	55	24	8 W 40 @ 4-1/2'	3"	3 x 3	4" Shotcrete	37
6	50	30	8 W 40 @ 4'	4"	2-1/2x2-1/2	4" Shotcrete	37
7	59	19	8 W 40 @ 6'	3"	3-1/2x3-1/2	3" $\pm$ Shotcrete (Avg.)	29
8	50	30	8 W 40 @ 4'	4"	2-1/2x2-1/2	2" Shotcrete & 8 W 40 @ 4'	40

* These are simple alternates - combination alternates were not determined because of the large number of possible combinations.

Figure 6.1

FIELD CASE STUDY NO. 2 - CUAJONE TUNNEL NO. 4							
STUDY SECT.	PREDICTED		PREDICTED SUPPORT ALTERNATES*B			ACTUAL*E SUPPORTS	ACTUAL EQUIV. RR
	RSR	RR	STEEL RIBS	SHOTCRETE THICKNESS	ROCK BOLT PATTERN		
1*A	50	30	8 W 31 @ 5' o.c.	3"	1" @ 3 x 3	Ribs 100%	32
2	61	17	Not Req'd	3" (For 50%)	1" @ 4 x 4 (For 85%)	Ribs 20% R.B. 12%	7
3	44	39	8 W 31 @ 4' o.c.	4"	Not Recommended	Ribs 73% Sh./R.B. 19%	20
4	65	13	Not Req'd	3" (For 40%)	1" @ 4 x 4 (For 50%)	Sh. 5%	2
5	44	39	8 W 31 @ 4' o.c.	4"	Not Recommended	Ribs 27% Sh./R.B. 87%	30
6*C	65	13	Not Req'd	3" (For 40%)	1" @ 4 x 4 (For 50%)	Ribs 11%*D Sh./R.B. 76%	27*D
7	39	48	8 W 31 @ 3' o.c.	4"	Not Recommended	Ribs 84% Sh. 100%	51
8	65	13	Not Req'd	3" (For 40%)	1" @ 4 x 4 (For 50%)	Ribs 5% Sh./R.B. 39%	14
9	39	48	8 W 31 @ 3' o.c.	4"	Not Recommended	Sh. 100%	33
10	65	13	Not Req'd	3" (For 40%)	1" @ 4 x 4 (For 50%)	R.B. 56% Sh. 52%	28

Notes:
*A - Estimated geologic sections; actual section lengths vary.
*B - These are simple alternates - numerous combinations are possible.
*C - Unanticipated Fault zone (#6A) found 450' supported by ribs and shotcrete. Actual RR of #6A = 52.
*D - Not including #6A (For #6 & 6A combined RR = 29)
*E - End of tunnel completed to July 1, 1973.
*F - Average steel ribs 8 W 20 @ 4' o.c.; average shotcrete 3" thick; Rock Bolts 1"@ 4 x 4

Figure 6.1 (continued)

FIELD CASE STUDY NO. 3 - CUAJONE TUNNEL NO. 5							
STUDY SECT.	PREDICTED		PREDICTED SUPPORT ALTERNATES*D			ACTUAL *E SUPPORTS	ACTUAL EQUIV. RR
	RSR	RR	STEEL RIBS	SHOTCRETE THICKNESS	ROCK BOLT PATTERN		
1 *A	55	24	8 W 31 @ 7' o.c.	3"	1" @ 4 x 4	Ribs 33% Sh. 83%	33
2	65	13	Not Req'd	3" (For 40%)	1" @ 4 x 4 (For 60%)	Ribs 2% Sh./R.B. 26%	8
3	39	48	8 W 31 @ 3' o.c.	4"	Not Recommended	Ribs 100% Sh. 40%	47
4	65	13	Not Req'd	3" (For 40%)	1" @ 4 x 4 (For 60%)	Sh. 30% R.B. 15%	13
5	39	48	8 W 31 @ 3' o.c.	4"	Not Recommended	Ribs 100% Sh. 100%	66
6 *B	65	13	Not Req'd	3" (For 40%)	1" @ 4 x 4 (For 60%)	Sh. 50%*C R.B. 6%	19 *C
7	39	48	8 W 31 @ 3' o.c.	4"	Not Recommended	Ribs 100% Sh. 100%	59
8	65	13	Not Req'd	3" (For 40%)	1" @ 4 x 4 (For 60%)	Ribs 7% Sh. 70%	23
9	39	48	8 W 31 @ 3' o.c.	4"	Not Recommended	Ribs 100% Sh. 100%	47
10	45	37	8 W 31 @ 4' o.c.	4"	Not Recommended	Ribs 45% Sh. 95%	41

Notes: *A - Estimated geologic sections; actual section lengths vary slightly.
*B - Unanticipated Fault zone (#6A) found. 200 ft. supported by ribs & shotcrete
Actual RR of #6A = 51
*C - Not including #6A (For #6 & 6A combined RR = 24)
*D - These are simple alternates - numerous combinations are possible.
*E - Average steel ribs 8W20 @ 4' o.c.; average shotcrete 3" thick; Rock Bolts 1"@ 4 x 4

Figure 6.1 (continued)

FIELD CASE STUDY NO. 4 - WASHINGTON METRO - SECT. 1A0061						
STUDY SECT.	STATIONS	CROSS SECTION	COMPUTED RSR	PREDICTED SUPPORT ALTERNATES		
				STEEL RIBS	SHOTCRETE THICKNESS	ROCK BOLT PATTERN
1	118+50 119+50	Transition	49	10 W 49 @ 4' o.c.	4"	Not Recommended
2a	119+50 123+50	Transition	53	10 W 49 Note A	4"	Not Recommended
2b	123+50 127+00	Twin Tubes	63*	Note B	2"	1" @ 5x5
3a	127+00 137+00	Twin Tubes	66*	Note B	2"	1" @ 5x5
3b	127+00 134+00	6x8 Pilot	56	4 I 7.7 @ 6' o.c.	1-1/2"	3/4 @ 4x4
4	137+00 156+00	Twin Tubes	71*	Note C	1-1/2"	1" @ 6x6
5a	156+00 171+00	Twin Tubes	86*	None Req'd	None Req'd	None Req'd
5b	164+00 171+00	12x8 Pilot	73	Note C	1-1/2"	1" @ 6x6
6	171+00 177+00	Twin Tubes	63*	Note B	2	1" @ 5x5
7a	177+00 206+00	Twin Tubes	71*	Note C	1-1/2"	1" @ 6x6
7b	198+00 205+00	12x8 Pilot	60	Note B	2"	1" @ 5x5
7c	195+00 196+00	Crossover	55	14 W 61 @ 3" o.c.	4"	Not Recommended
8	206+00 221+00	Twin Tubes	83*	None Req'd	None Req'd	None Req'd

Notes: * Includes TBM factor
A - Spacing varies from 5' @ 119+50 to 3' @ 123+50
B - Nominal support only - 6H15.5 @ 7'
C - Nominal support for 50% or less of section

Figure 6.1 (continued)

FIELD CASE STUDY NO. 5 - CARLIN CANYON TUNNELS

STUDY SECT.	STATIONS*	PREDICTED		PREDICTED SUPPORT ALTERNATES**		ACTUAL STEEL RIB SUPPORT	ACTUAL RR
		RSR	RR	STEEL RIBS	SHOTCRETE THICKNESS		
EASTBOUND:							
1	1777 + 44 1779 + 90	46	36	8 W 67 @ 3-1/2' o.c.	5"	8 W 67 @ 2-1/2' o.c.	56
2	1779 + 90 1783 + 90	52	27	8 W 67 @ 5' o.c.	4"	8 W 67 @ 5' o.c.	28
3	1783 + 90 1789 + 70	56	22	8 W 67 @ 6' o.c.	3"	8 W 67 @ 5' o.c.	28
4	1789 + 70 1791 + 70	41	44	8 W 67 @ 3' o.c.	5"	8 W 67 @ 2-1/2' o.c.	56
WESTBOUND:							
1	1777 + 79 1779 + 00	46	36	8 W 67 @ 3-1/2' o.c.	5"	8 W 67 @ 2-1/2' o.c.	56
2	1779 + 00 1781 + 80	52	27	8 W 67 @ 5' o.c.	4"	8 W 67 @ 5' o.c.	28
3	1781 + 80 1788 + 80	56	22	8 W 67 @ 6' o.c.	3"	8 W 67 @ 5' o.c.	28
4	1788 + 80 1791 + 40	41	44	8 W 67 @ 3' o.c.	5"	8 W 67 @ 2-1/2' o.c.	56

* Actual Stations Differed Slightly

** Rock Bolts not recommended because of vertical bedding and tunnel size

Figure 6.1 (continued)

FIELD CASE STUDY NO. 6 - NORAD EXPANSION							
STUDY SECT.	DESCRIPTION	SIZE & SHAPE (W x H x L)	PREDICTED		ESTIMATED PATTERN 1" ROCK BOLTS	ACTUAL ROCK BOLT PATTERN	ACTUAL EQUIV. RR
			RSR	RR			
1	Power Plant Chamber	67x53 (HS) x 189	70	8	4 x 4	(4.7x4.7) ÷ 2 *	14
2	Cooling Tower Chamber	38x45 (HS) x 185	63	15	3-1/2 x 3 1/2	(4.7x4.7) ÷ 2 *	20
3	Power Plant Access Adit	32x25 (HS) x 113	70	8	6 x 6	4.7 x 4.7	11
4	Exhaust Valve Chamber	20x27 (HS)x 140	63	15	4 1/2 x 4 1/2	4 x 4	19
5	Exhaust Delay Path	19 Diamx 374	63	15	5 x 5	4 x 4	24
6	Intake Delay Path	18 Diam. x 502	63	15	5 x 5	4 x 4	25
7	Cooling Tower Exhaust Tunnel	19 Diam. x 120	70	8	6 x 6	4 x 4	24

*2 Bolts used. (1 - #8 & 1 - #10 alternating) every 4.7 x 4.7. In all other sections only #8 bolts were used on given pattern.

Figure 6.1 (continued)

bolt supports are based on suggested relationships discussed in paragraph 5.5.

Length of individual test sections, size of tunnel and notations as to whether supported or unsupported are shown on Figure 6.2.

6.4 EVALUATION OF FIELD TESTS

A general appraisal of reliability occasioned by use of the prediction model can be made by plotting the actual or equivalent rib ratios for respective tunnel test sections vs. determined RSR values. Results are shown on the summary graph of the prediction model of Figure 6.3. It is seen that nearly all plotted points fall within the developed envelope and are generally above the statistical average curve used in developing the model. A possible conclusion based on this evaluation is that the prediction model is too optimistic - that is, it reflects lesser support requirements than actually needed. This is somewhat contrary to expressed concern that the prediction model would perpetuate the "over-supporting" of tunnels.

Other evaluations can be made by considering the actual or predicted lengths of supported or unsupported tunnel. (See Figure 6.2)

Total length of tunnel for which it was possible to compare predicted and actual support is 34,980 feet. Use of the prediction model indicated that approximately 23,265 feet would require support, the remaining 11,715 feet being unsupported. Corresponding actual lengths were 24,808 and 10,172 feet respectively. The overall predicted length of supported tunnel was 94% of actual though greater variations can be noted in individual

FIELD STUDY GEOLOGIC SECTIONS % SUPPORTED - PREDICTED AND ACTUAL						
FIELD STUDY	DESCRIPTION OF TUNNEL	GEOLOGIC SECTION			% SUPPORTED	
		NO.	LENGTH (FT.)	SIZE (FT.)	PRED.	ACT.
F-1	New Melones	1	280	30 x 34 HS	100	100
	U.S. Corp of Engineers	2	180		100	100
	California - D&B	3	960		100	100
	Length 3,770'	4	60		100	100
		5	660		100	100
		6	600		100	100
		7	800		100	100
		8	230		100	100
F-2	Cuajone No. 4	1	150	24 x 22 HS	100	100
	Southern Peru	2	750		50	46
	Copper Company	3	2000		100	70
	Peru - D&B	4	1100		40	5
	Length 19,200'	5	3000		100	77
	(as of July, 1973)	6	6400		40	75
		7	300		100	100
		8	3300		40	38
		9	300		100	100
		10	1900		40	73
F-3	Cuajone No. 5	1	300	24 x 22 HS	100	87
	Southern Peru	2	1500		40	22
	Copper Company	3	100		100	100
	Peru - D&B	4	1600		40	40
	Length 7,600'	5	100		100	100
		6	1100		40	64
		7	100		100	100
		8	2000		40	66
		9	100		100	100
		10	700		100	96

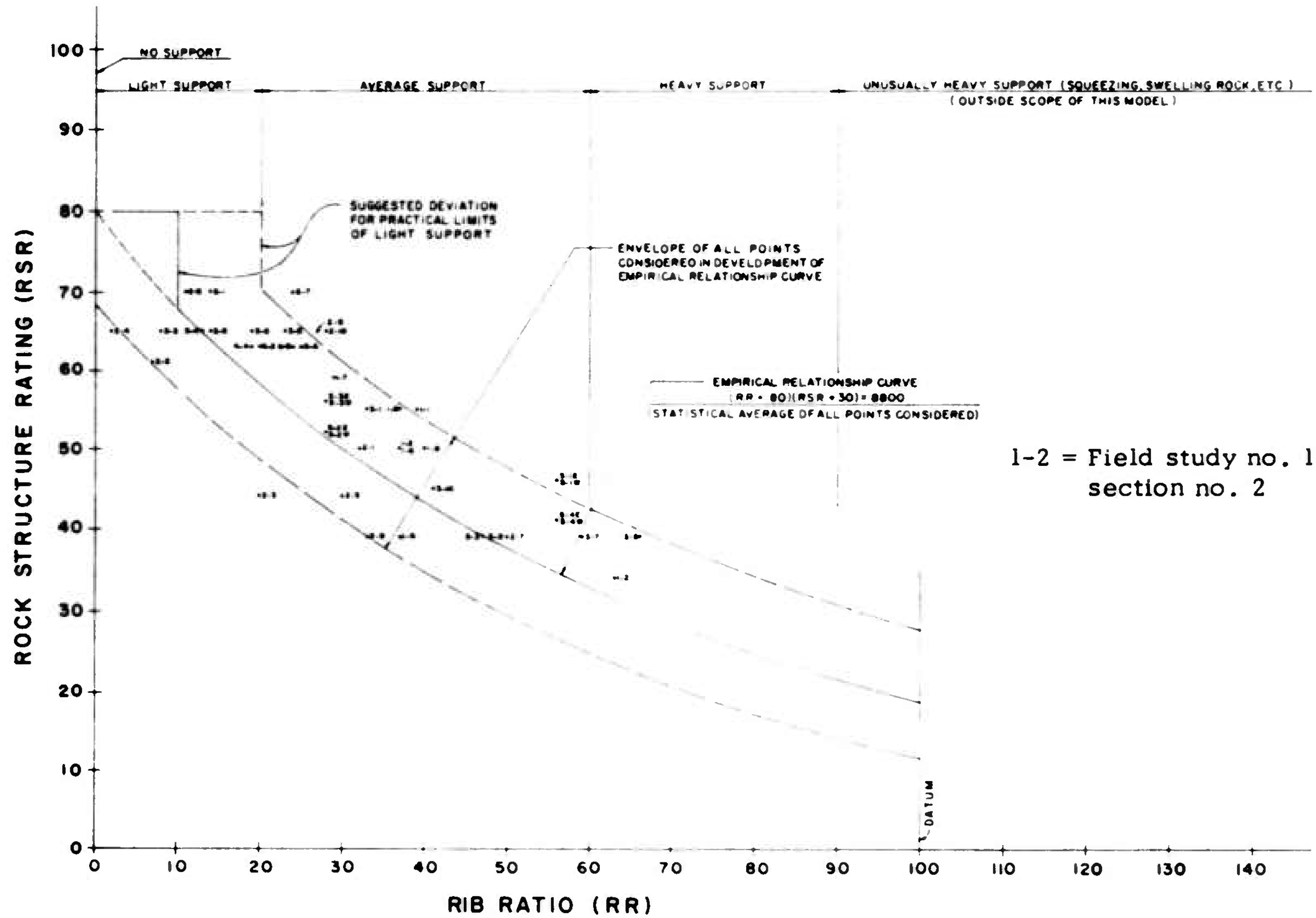
Figure 6.2

FIELD STUDY GEOLOGIC SECTIONS % SUPPORTED - PREDICTED AND ACTUAL						
FIELD STUDY	DESCRIPTION OF TUNNEL	GEOLOGIC SECTION			% SUPPORTED	
		NO.	LENGTH (FT.)	SIZE (FT.)	PRED.	ACT.
F-4	Wash. Metro IA0061	1	100	30 x 21 HS	100	*
	Washington Metropolitan Area Transit Authority	2a	400	44 x 27 HS	100	
		2b	350	2 @ 19 Dia	100	
	Washington, D.C. - T.B.M.	3a	1000	2 @ 19 Dia	100	
	Length 22,200'	3b	700	6 x 8 HS	100	
		4	1900	2 @ 19 Dia	50	
		5a	1500	2 @ 19 Dia	0	
		5b	700	12 x 8 HS	50	
		6	600	2 @ 19 Dia	100	
		7a	2900	2 @ 19 Dia	50	
		7b	700	12 x 8 HS	100	
		7c	100	58 x 30 HS	100	
		8	1500	2 @ 19 Dia	0	
F-5	Carlin Canyon	E-1	246	38 x 31 HS	100	100
	Nevada Department of Highways	2	400		100	100
		3	580		100	100
	Nevada - D&B	4	200		100	100
		W-1	121		100	100
	Length 2,787'	2	280		100	100
		3	700		100	100
		4	260		100	100
F-6	NORAD Expansion	1	189	67 x 53 HS	100	100
	U.S. Corps of Engineers	2	185	38 x 45 HS	100	100
		3	113	32 x 25 HS	100	100
	Colorado - D & B	4	140	20 x 27 HS	100	100
	Length 1,623	5	374	19 Dia	100	100
		6	502	18 Dia	100	100
		7	120	19 Dia	100	100

D & B = Drill and Blast
T.B.M. = Tunnel Boring Machine

*Not yet excavated

Figure 6.2 (continued)



Field Test Sections Plotted on RSR-RR Graph

Figure 6.3

sections.

Another comparison can be made by extending respective rib ratios (predicted and actual as discussed in paragraph 6.3 and shown on Figure 6.1) against corresponding lengths of applicable sections expressed as a percentage of the total length of supported tunnel. Since rib ratios basically define the physical properties of the respective support systems (size and spacing of ribs, thickness of shotcrete, etc.) it provides a fairly realistic appraisal of the overall support requirement. Results of this computation are given below:

Project	Average R.R. Predicted	Average R.R. Actual
1 New Melones	28	37
2 Cuajone #4	36	37
3 Cuajone #5	35	38
4 Washington Metro	-	-
5 Carlin Canyon	29	36
6 Norad Expansion	13	21
All Projects	32	36

The overall prediction of support requirements was approximately 89% of actual, or expressed otherwise, the total quantity of support (pounds of steel ribs, cubic yards of shotcrete or number of rock bolts) as may have been determined by use of the prediction model would have been approximately 11% less than actually used.

Although the above evaluations show a fairly high degree of relia-

bility in using the model, a comparison of predicted and actual rib ratios for individual tunnel sections (see Figure 6.1) may show rather large discrepancies. This is due primarily to basic methodology used in developing the model, wherein a statistical average of case history data was used to establish the empirical relationship between rock structure and ground support. Although a rib ratio defined by a determined RSR value reflects the statistical average, it can be seen by the graph of Figure 5.4 that the rib ratio for any particular RSR value could vary between limits of the developed envelope. This might be construed as a weakness of the model, but until the prediction of sub-surface conditions becomes an exact science it must be accepted that the determination of ground support for future tunnels will continue to be a "qualified art". It is both desirable and likely that by continued use of the model the width or range of the enclosing envelope will be narrowed so that more definitive answers can be obtained. In essence, this reflects the initial intent in that the prediction model is not intended to be an exact measure of a particular support member at a specific tunnel location but rather to provide a realistic appraisal of the overall support requirement. The tabulation on page 6-20 shows that although there were differences for individual tunnels, the overall prediction of support requirements substantially agreed with actual installations.

The Support Requirement Charts generally indicate three alternative support systems which could be used for a particular tunneling situation. The most appropriate being determined by individual analysis. Although this

multiple choice approach is typical of all prediction methods, it would be desirable if guide lines could be established which would enable potential users of the prediction model to pick that system which would most likely be used. The field studies also indicated the use of "combination support systems", which are not specifically included in the prediction model. Correlation between these combination systems and the prediction model can be made by calculation, as discussed in paragraph 6.3. It may be preferable, in the future, to include a limited number of representative support combinations in the support requirement charts.

6.5 CONCLUSIONS

Although it is realized that the limited number of tunneling situations considered are not sufficient in themselves to make final conclusions, it does appear that realistic predictions of ground support requirements can be made by use of the RSR model. This is further evidenced by similar results obtained from the second year case history studies which were essentially treated as on-going projects. Within limits of present day sub-surface investigations, and the model itself, it would be unreasonable to assume or expect a reliability requirement of 100%. Whether the reliability criteria should be plus or minus 10% or even 20% is hard to say, but any method which would provide consistant results within the above limits would be substantial improvement over the present state-of-the-art. The field experiments show the reliability of the proposed prediction model to be in the general range of minus 10% with respect to actual requirements. If con-

tinued testing shows similar results, the basic empirical relationship between RSR values and rib ratios should be modified and Support Requirement Charts adjusted accordingly. Due to the manner in which the model was developed, checked and verified by this and the previous research effort, such refinement at this time is not warranted.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The ground support prediction model (RSR concept) provides a standard approach and realistic solution to a complicated problem. It includes and evaluates those geologic and construction factors most pertinent to the determination of ground support and which are usually available for consideration in the pre-construction period. The format and procedures used to predict the competency of rock structures and support needs along the tunnel line are expressed in common terms and presented in a straight forward manner readily adapted to initial planning, design, and costing, of future tunnels, and field implementation during construction.

The model developed can be modified or adjusted as needed to properly reflect findings and/or determined correlations between predicted and encountered conditions that may result from continued use, research or testing efforts.

The model provides a more definitive description of commonly used support systems (steel ribs, shotcrete, rock bolts) than obtained by use of existing methods. Most existing rock classification systems, although geologically detailed, give only general recommendations for "light", "medium" or "heavy support."

Initial testing by field application to several on-going projects

indicate that realistic appraisals of ground support requirements of future tunnels can be made by use of the prediction model.

Due to differences in construction requirements and overall methods of operations, the prediction model is generally more applicable to civil works than to mining applications.

Until such time that advanced geophysical or remote sensing techniques can define exactly sub-surface conditions, the "art" of predicting ground support will depend primarily on the qualified judgement of involved disciplines with respect to findings of actual construction and theories of geology and rock mechanics. The systematic correlation of judgement and physical data afforded by the proposed prediction model is a significant improvement to the present state of the "art". Continued use and subsequent testing in either civil or mining operations would soon lead to a useful, reliable tool for practical usage by the tunneling industry.

One of the greatest pitfalls in developing a reasonable prediction model, and one which hopefully the RSR concept will help to eliminate, is the ever present tendency of attempting to minutely define the large number of variables which are or could be involved in evaluating the competency of a rock structure. Although volumes have been written which fully describe the sciences, theories and complexities of geology and rock mechanics, existing results pertaining to the prediction of ground support can be categorically described as "Good rock = no support", "Bad rock = support". This expression is slightly pragmatic and is intended not as criticism but

rather to point out the necessity of developing, at some point in time, a common standard or approach that would provide realistic answers. No method, whether consisting of numerical parameters or lengthy technical descriptions, would be completely adequate for all situations.

7.2 RECOMMENDATIONS

Acceptance of the ground support prediction model by the tunnel industry will depend largely on validity of results as obtained by field application. Although case history data is meaningful, it cannot be considered the same as actual experience. Unfortunately, current or planned tunnel projects in which the model could be tested are fairly scarce at the present time and usually are of such magnitude that results would not be known for some time. Without discouraging maximum field implementation, it is recommended that the following areas be investigated, all of which would contribute to and encourage usage to increase confidence in the prediction model.

1. Compare factors and conclusions derived from the RSR concept with results obtained from other methods of predicting ground supports, such as Deere's (5), Terzaghi's (6), or Wahlstrom's (7); or from various analyses based on the theory of rock mechanics.
2. Correlate anticipated rock loads (Wr) as identified by predicted RSR values with loads determined from in situ or laboratory testing procedures.

3. Relate RSR values to a "drillability" factor in conjunction with potential use of a tunnel boring machine.

4. Establish guide lines by which the most appropriate of possible alternative support systems can be identified.

5. Develop RR correlation between combination support systems (shotcrete, rock bolts, etc.) and RSR predictions.

6. The Bureau of Mines is encouraged to promote and sponsor additional research in the field verification of the RSR and RR with particular emphasis given to instrumented rock, support, and rock-support interaction data.

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APPENDIX "A"

INDUSTRY'S COMMENTS REGARDING

GROUND SUPPORT PREDICTION MODEL

(RSR CONCEPT)

This appendix contains a general summary of comments regarding the RSR concept of predicting ground support as received from members of the tunneling industry. They are grouped in accordance with numbered sections of the questionaire as shown in Section 4 of the report. As explained in Section 4, this questionnaire was sent to selected representatives of the tunneling industry for a critical review of the RSR concept. The names of individuals quoted have been omitted to avoid any misunderstanding that might arise from taking quotes out of context. Names of all respondents are given in Section 4.3.

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APPENDIX A

INDUSTRY'S COMMENTS REGARDING

GROUND SUPPORT PREDICTION MODEL

(RSR CONCEPT)

A.1 General Comments

"A few of the questions were a little ambiguous."

"I believe you have hit on the basis for a fairly useful technique."

"I believe you have a very interesting concept and one which should be workable. Its application is simple enough that supervision at the tunnel heading can use it without waiting for an engineer or geologist to interpret conditions. Only experience with its application will prove its value. It is too bad that this concept was not developed years ago as I would have liked to try it out on some of our tunnels based on my thirty years experience."

"I wish I had the confidence in our surface geology and its projection to tunnel level to use the RSR system."

"There are many alternatives and you have to select the right one."

"My responses are colored to some extent by my experiences and comparisons. Some of my thoughts regarding the influence of joint orientation and character of the joints are summarized."

"Your work has stimulated my thinking and I want to spend more time comparing your rock loads with some of our rock load predictions".

I replied to your questionnaire to the best of my ability."

"I am confident that the final results will be very useful in evaluating the Rock Structure Rating."

"My answers to your questions reflect my opinion on the start-of-the art of tunnel geology in a manner that will serve as a guide in refining a very useful contribution to tunneling technology".

"Please pardon my delay in completing your questionnaire as I have been busy trying to resolve with the owner the problems of adequate support for a project."

"The use of such a method within the industry would be beneficial to everyone so involved. It has long been my contention that too little time and money are spent to obtain geological information and evaluate it properly prior to the design phase and preferably prior to the taking of bids. Any innovation which will reduce the guess work involved will benefit both the owner and the contractor and cannot help but improve relationships between the owner and the public who in the final analysis foot the bill."

"In our use of the concept on a current tunnel contract it has been found to provide quite reasonable correlation with measured set loads (50 sets monitored)."

"Geology is more complex than the support system requirements; therefore, many different ground conditions can be supported by the same support system."

"The estimates and numerical values assigned to each rock type are dependent upon the accuracy and availability of preliminary geologic information. It would require more emphasis be placed on accurate geologic mapping, joints, fractures and other rock defects."

"The legal involvements of a tunnel owner preparing and making available this information would have to be investigated. This may be another tool for contractors to sue for changed conditions based on geology again."

"The report is based on 33 case history studies. Support in any tunnel is still based upon the experience and judgment of the contractor building the tunnel. The only way of telling if a tunnel is unsupported is by failure of the support system. Because of this, most tunnels are probably oversupported. The Jacobs report takes a theoretical numerical value and assigns it to a rock type. The accuracy of this method is dependent upon the experience and judgment of the person utilizing this method."

"This report would be a useful tool in preliminary estimates on tunnel costs. It could be used for cost analysis of different tunnel routes if comprehensive preliminary geologic studies were done. I doubt if this method could be used to prove either oversupported or undersupported tunnels and it is probably best used for preparing bids. Engineers may read and utilize the RSR evaluation, but I doubt that you could get experienced tunnel contractors and miners to abandon their "art" of deciding tunnel supports."

"In general, I like the method used. It assigns numbers to rock types and gives the engineers something to understand. This is another step, like RQD, in giving numbers to rocks."

"The report is very interesting, principally from the fact that an empirical method is developed for design of rock supports. You people do have a lot of

experience and no doubt your procedure bears looking into."

"In your conclusions and recommendations you go back to needing better geology, better handling of the data, and better retrieval systems which basically comes back to the same thing, the struggle was at the beginning. There isn't any good system for tunnel design, and the report indicates there isn't going to be a good one in the near future other than an empirical method."

"It is difficult to accurately report on your rock structure evaluation because factors other than geology affect the amount and type of tunnel support. This is further complicated because a substantial portion of the basic data used in the development of the rock structure rating concept contains example tunnels in which the quantities of support do not necessarily relate to geologic conditions."

"As you can see from my answers, I am skeptical as to the likelihood of accurate support prediction by the use of any rating system."

"I am of the firm opinion that the more information that is provided during the bidding period, the less changed condition claims will be filed. This is why systems such as yours on rock structure rating and rib ratio concepts must be developed and used on underground construction."

"I regret the delay in completing your questionnaire, but felt compelled to hold off until I could competently submit a reply."

"You have done much to convince me that there may be a way of weighting the experience we call geologic engineering judgment. I expect more uniform results for more equitable tunneling conditions under the most varied of tunneling conditions encountered world-wide."

"The RSR as I view it does not speak to the extremes, which are the most difficult and most critical of the tunneling conditions; such as "squeezing", "swelling", and "running" ground. These would be most useful to the industry. The hardest, soundest and best granite tunnel does not need more than a statement to that affect by a competent geologist from conception through construction yet the RSR speaks best to these conditions."

A.2 Answers to Question I-3:

"..... general description of ground water table -- and major faults -- strike and dip of formation."

"..... portal drilling if portal is in overburden, plus surface mapping along the route."

"..... all geologic boring logs, geophysical surveys, surface geologic information, laboratory tests on rock defects, all ground water information, laboratory tests on rock defects, all ground water information, plus any nearby experience."

"Careful, professional geological mapping with aid of remote sensing imagery. Core drilling and geophysical investigation as required or economically feasible."

"A geologic report of area to be penetrated including a geologic map with emphasis on structural features of formations."

"Geological reports and maps; with comparison to jobs in similar geologic environments; some subsurface exploration with detailed study, description and report on core logs; ground water information."

"Regional geologic framework, including tectonic activity. Rock types and elements of rock competency, determined from surface (outcrop) and core hole samples."

"Reference to other tunnels, cuts, slips, and groundwater conditions in area. Continuous core samples (logged) with classification logs of borings showing observed joint patterns, dip, strikes, etc. Geologic profile based on actual samples, observation, and classification. Ground water location, temperature, flow, pressure loss, and pump tests. Lab tests of hardness, compressive strength, and shear."

"Drill logs of all exploratory holes, rock type, fracture spacing, water flows, water table level, weathering."

"A geological section along the center line showing boundaries of different types of ground with conclusions as to anticipated conditions whether favorable or unfavorable."

"Detailed surface geology. Vertical borings and logs at critical locations such as adit intersections unless rock is massive and does not warrant drill holes."

"Borings, cores, existing geological maps, typical supports in similar tunnels in nearby area."

"Type of rock, rock strength, joint planes, water flow, nature of rock, cores (and borehole logs), rock structure."

"The prebid geology report should explain the limitations and assumptions."

"At lease a reliable estimate of quantities are needed, and in known problem

areas, the contractor should be told what support is required. However, support locations cannot usually be given exactly for a long tunnel -- this could result in changed conditions."

"Heading support of overriding significance in a full-face tunnel."

"Legal, contractual, and tradition unfortunately receive too much attention."

"None! however, when 'none' is provided then more must be done and it may take longer to make a realistic geologic appraisal for bidding. Contract conditions must also be studied differently. If both are available -- then borings and logs = 1; because it is possible to get some surface geology more readily than boring data within the limited time available."

"Geologic profile along proposed alignment. Lithologic classification. Tunnelman's Ground Classification."

"1. Core study. 2. Drillers' logs. 3. In-hole water pressure tests. 4. Oriented core summary. 5. Air photos. 6. General geology -- previous studies in area. 7. Available data on nearby tunnels. 8. Map of surface exposures, geologic data in vicinity of tunnel line. But emphasize major factors. (Information to be used in bidding a job: Much of this could be provided by the engineer (owner's representative) in a prebid geology report.)"

"Vertical borings on 1,000 foot centers. Surface geology. As-built geology."

"Mineralogy, structure, genesis, and geologic history of rock. Quantitative definition of structure, its dimensions frequency, and attitude." "General geology including basic ground water data, surface mapping if practicable, cores and detailed geology at portals as practicable, drill logs and core samples of rock along tunnel alignment determined by design requirements."

"Borings with complete geological interpretation of them by engineering geologists."

"Lithology, ground water, joints (and filling), and major faults."

"Geologic classification (sedimentary, igneous, metamorphic), chemical data, mineralogical, e.g. the effect of exposure to the atmosphere, the effect of water, joint orientation and pattern."

"Core logs, samples, and geologic maps."

"Geologic map and cross section, written geologic report, logs of borings (including reasons for poor core recovery), as-built geology of nearby tunnels."

A.3 Additional comments on Part I

"In many situations, explorations ahead of the tunneling operation are a must. These have been largely ignored except for work of Tom Williamson."

"Answers entirely depend on contract conditions. The basis for the engineer's estimate should be provided. Answers dependent on whom it is intended that the cost of over-runs is to be borne."

"Projection of surface geology to tunnel grade depends on many variables, some unknown. Guesswork in projections serves no good purpose."

"The owner has had the most time to expend effort to explore and design tunnel, therefore, his basis for design should be available to bidders. However, with regard to Questions 6 and 7, revealing these data should not be a basis for changed conditions unless there are gross differences in conditions requiring changed driving method and support type."

"Each project should be classified into a geologic structural province according to present tectonic stress, depth of cover and past structural-tectonic history; temper this with effect of ground water and blasting and the support picture shapes up quickly."

"The Rib Ratio doesn't allow for less actual support than theoretical support, i.e. RR greater than 100."

"Give contractor choice of type of tunnel if possible, such as circular, horseshoe, top heading and bench."

"Many of the questions on this questionnaire go beyond geology and should rightly be put into the context of the geology of the project and the contract documents in order to make them realistic and germaine to this important subject."

"The owner's geologists should be more qualified on these local geologic conditions than others. Also, the contract documents should stand squarely behind those predicted projections. The owners would get work at less cost and with more equitable bidding, because of removal of some of those contingencies which more correctly belong to owners than to the constructors bidding that work."

"Only where geologic data are highly definitive but not where, as is the common case for long tunnels under deep cover, the interpretation of tunnel grade conditions is speculative."

"The factors affecting support placement vary from tunnel to tunnel."

"Magnitude of in-situ stress, if any, should be determined when possible."

"A rock mechanics classification system similar to the classification system used in soil mechanics is needed."

"Geological investigation methods which are faster should be developed for deep-lying tunnels."

"When the type, spacing, and location of support is included in pre-bid documents, the owner is taking on the risk."

"Exploratory drifts would be most desirable for pre-bid work."

"All reports and conclusions should be in tunnel layman's language. Effort and money spent on pre-design and pre-bid geological information will reduce project cost and construction by many times."

"Actual ground requirements were interpreted as geological considerations."

"I am in favor of complete pre-bid geologic reports as part of the contract documents (or referenced). I do not believe that there is much evidence that such information (carefully prepared) will hurt the owner. Many claims stand because quantities and design are inadequate, not because of changed geology. If there is a real changed geology, then the pre-bid report will help make the settlement equitable."

"Supports are often installed unnecessarily simply because 'he has the steel ordered and the gang organized' and he is being paid for it."

"A major problem in estimating tunnel support is making quantitative measurements of geology at the surface, and the reliability of the projection of these very limited data to tunnel level."

"Expedient refers to contractor's profit margin on steel ribs."

"All available factual data should be given to all bidders without comments, opinion, conclusions or predictions by the owner."

"Improvements in Tunnel Support Prediction techniques can be made gradually so that the support requirements are more in keeping with ground conditions and less dependent on other factors."

A-4 Comments on Part II - Geologic Factors

"If possible, any knowledge of 'locked-in' stresses in the rock prior to excavation would be helpful."

"In general, quantitative data is preferable to qualitative data."

"Need explorations ahead of the face for very deep tunnels to ferret out rock defects and rock conditions not predictable from above."

"I have never worked on a long tunnel where detailed, quantitative prediction of geologic conditions at depth was possible."

"Each excavation site would probably have different emphasis on geologic factors depending on rock type and geologic structure."

"The geology cannot be too well explored and known. Core logs should be detailed, complete, and well explained. The man logging the holes should be a geologist well experienced in coring techniques. This information is basically what the support system will be based upon."

"Once you get into quantitative fields, the owner opens himself to claims."

"Other wear parameters relating to drillability particularly with reference to machine tunneling could be included in mechanical properties."

"There is no point in separating joint orientation and joint pattern."

"Geologic structure means too many different things."

"Rock type question -- I presume subdivision refers to petrologic nomenclature, such as andesite, sandstone, etc."

"Ground water flow -- the data is limited to ground water levels, standard water tests, and pump test results without quantitative evaluation."

"I have used a category which may be termed "joint prominence" or 'joint rank.' This is a measure of the continuity and how extensive the joint or joint set is, i.e. local or widespread. This information aids in estimation of water inflow and stress-structural influence."

"The degree of weathering or alteration (WA) and the condition of the joint surfaces (JS) are the two most important considerations to me, but when neither are present as is true under some geologic conditions, then the joint orientation in relation to the direction of driving becomes a major factor particularly for TBM considerations."

"Perhaps more information on the mechanical properties could be made available by laboratory testing of samples. Particularly the reactions of the rock when relieved of its stresses, temperature, moisture content."

"Quantitative measurements, not relative terms, should be used to describe

geologic factors."

"(Joint spacing) A and B are the same: 'Blocky' is used in general discussion but blocky is usually defined in reports as to exact joint spacing."

"In the future, with more knowledge gained by tunnel people, I believe qualitative descriptions will be used more extensively."

"Geologic factors are very difficult to rate without an in-depth study. The rating of your report (Table 1) is acceptable to me as a general rule. Under certain conditions the maximum values could change; for instance, should the geology be massive or faulted granite the effect of water in-flow or joint seal is minimal, however, the reverse could be true with a different geological formation."

"The bore size has a great deal to do with support requirements within the same formation. In massive rock, the bore size would have little effect. In badly fractured rock, including granite, or weaker rock, the bore size is often the controlling factor. Your empirical formula and resulting curves seem to adequately provide for this effect of bore size."

"I believe that the quantification of geologic factors and their effect on tunnel supports can be made more rational and uniform with the use of appropriate classification schemes."

"Often helpful to know the history and character of a specific formation."

A.5 Comments on Questions III - 2 & 8 - Support Prediction Model

"It is a commendable effort."

"There is a danger in extrapolation from data that often are qualitative. Personal judgment based on experience and honest indication of what is not known is essential."

"Regards Question 6 -- general relationships can be developed, however, I doubt that one set of values would have universal application. I believe that each job is unique and within certain limits, different weighted factors would apply to have reliable predictions."

"Data banks would be helpful and must be composed of uniformily collected and treated data. Field data are seldom in the same ball park with lab data in this regard."

"I would rely most heavily upon the quality of drilling, the quality of geology and the total investigations done by others and then add to their data factors

which are most significant and critical in terms of my own site appraisal and then render the sum total of these as my best judgment in terms of the contract conditions. It is the experience of the geologist which is the 'data bank' weighting different factors and conditions for the tunnel that must be most heavily relied upon to communicate and equate this information in terms of a meaningful support prediction model for that tunnel."

"The Support Prediction Model as conceived, is certainly applicable to circular underground excavation. However, it must be recognized that additional factors are required to determine support for other than circular geometric sections of excavation."

"The most important geologic factors in determining support requirements are, in order of importance: 1. Size of rock fragment that must be supported, 2. Compressive strength of rock mass in relation to tunnel dimensions, etc., 3. Mineral composition and behavior of minerals under environmental conditions, 4. Attitude of discontinuities in relation to axis of tunnel, 5. Ground water, 6. Fracture fillings. These factors must be predicted at tunnel level based on geologic and geophysical investigations at the surface, physical exploration, and field and laboratory testing. The compilation of data, extrapolation into covered areas, and projection of the data to tunnel level is the most difficult -- or can be done with least reliability. The correlation of support requirements with geologic factors on an "as constructed" basis can (and should) be done for each tunnel with a high degree of reliability or confidence. The definition of the geologic factors at tunnel level prior to construction -- not their influence on support requirements -- is what is most difficult, and is where the greatest error is introduced in design requirements and estimates of cost."

"No place for squeezing ground or unusual adverse condition. Sedimentary rock is too broad a classification -- degree of cementation, type of cementation, friability should be used in classification. Parameter A is too general -- e.g., limestone can be close to a soft marl or a hard marble."

"I rated the way it is because past experience on tunnel supports best takes into account the factors in question. Certainly a theoretical analysis of rock mechanics cannot take into account such reasons."

"The detail design based on the RSR Concept could be refined so as to make it more useful to the industry."

"Reference Parameter 'A'. The basic type of rock has little significance on support requirements. Information on the intensity of rock defects (dimensioned on a numerical scale) is more important than the type of rock that may be encountered."

"Parameter A: I can see some advantage to use of such a parameter, but I

know of an intensely folded rock - Manhattan schist - which has wavy joints, surfaces, and shears which requires little support. In Washington, the rock has been intensely folded, but has very continuous planar joints. Support conditions are much more difficult. I like the idea of joint orientation (Parameter B). There will be some difficulty in long tunnels where joint (strike) orientation wanders, or is not easily predictable. I would place more emphasis on the character of the joints.

"Anything is better than the present 'Rule of Thumb'."

"RSR parameter weighting often must depend on subjective evaluation."

"The values you show in Table I are acceptable to me. A detailed in-depth study might change my opinion."

"I'm not sure it can be done with one rating. At least, I would like to use the major parameters separately in evaluating the load, and even in estimating support."

"It is assumed that question 7 means in addition to competent geologic investigation."

"Present support design is too conservative -- with better prediction, support could be designed more rationally."

"Anticipated support requirements should be adequately and clearly defined in pre-bid documents. If actual requirements are greater, there should be compensation."

"Rock properties should be better defined from the rock mechanics point of view, i.e. uniaxial compression, strength of rock substance, failure characteristics."

"I believe tunnel support requirements should be adequately and clearly defined in pre-bid contract documents. Actual ground requirements may change the amount of supports actually used but the contractor, cr the owner, must be compensated for the difference. Hence I agree with the concept of a 'support prediction model.'"

"Amount of surface cover and quality of investigations."

"To broaden your classification I recommend inclusion, perhaps seperately, of dynamic factors such as fault movement likely during life of project and earthquake hazard. The static aspects of rock masses are well covered; the dynamic aspects are not."

"The geometry of the structure is of prime importance. The hazard of exposure

due to time between excavation and completion of structure."

"Additional factors are not required, but the basic factors which have a direct bearing on support requirements should be put into a common perspective."

"Not entirely; joint continuity planarity, filling."

"Alluvium should be included under rock (soil) types."

"Effect of in-situ stress field or an estimate thereof from adjoining mountains."

"In urban areas (for Rapid Transit) surface geology may not have been mapped before urbanization and few outcrops are available now. Then you would have to rely on historical -- structural geology."

"Depends on complexity of geology. For simple geology: yes. For complex geology: no."

"But we do not take advantage of the available methods nor do we adequately interpret geologic information that is obtained. We should obtain 100 percent of core recovery and should know orientations of structures."

"In near-surface tunneling (cover less than 100 feet -- yes, if structure is simple and consistent; no, if complex structure and cover greater than 100 feet."

"It should be, for cost estimates, but no matter how well intentioned this information might be, it only causes contractual problems later and 'change of conditions' claims.

"In-situ testing has not been taken into consideration because it is not extensively employed; however, a factor that might be developed at a later time. Deformation rate and support load factors as possibilities for heading support modification."

"Use term RSR as Rock Support Rating rather than Rock Structure since geologists use the word structure in a different context."

A.6 Comments on Part IV - Acceptability of Proposed Rock Structure Rating Method

"If half the supports are put in for reasons other than ground loading, a rating based on historical data may tend to perpetuate over-design. I am also concerned as to the projection of historical data into new methods -- such as machine excavation."

"Based on past experience, engineers and contractors accept new ideas and change very reluctantly. A real selling job will be required for general acceptance. Until more accurate geological data is available and tied to how it can applied to support needs, acceptance will probably be on limited scale."

"No two tunnels are exactly alike. Each must be analyzed separately. Even then, tunnel construction must be fought out at the heading. The ideal goal would be to have a machine and support system which can handle all ground conditions expected to be encountered. I think it would be interesting to combine all the various attempts at classification, by Deere, Stini, Lauffer, Aufmuth, Handewith, Bureau of Mines, Bureau of Reclamation, Brekke, Goodman, O'Neil, and others just to see if an ideal classification could be developed."

"As for any rating scheme, the quality and quantity of the input are of prime importance. Tunnel geology ranges from simple to extremely complex and rarely is the budget for investigation adequate to supply answers to many critical questions. Tunneling is still mainly an art."

"Any techniques developed for obtaining rock load would be indirect methods, subject to verification. RSR concept would be a way of testing to increase confidence factor of instrumental data."

"It was with some consideration and thought that I answered this questionnaire. However, it made me think of a questionnaire sent to me some years ago, to sample the reading tastes of subscribers to periodicals. When I had finished, I found that I had not only convinced myself that I should subscribe to a periodical, but that it should be (Life, Time, etc.) and for 3 years! Somehow I feel now that I have subscribed to something here that does not completely consider the way the specs and contract are written and that money is the real objective and this affects many relationships. If the RSR works and is accepted by most -- that's fine, but its first failure, resulting in much greater costs, affects everybody and damages the concept."

"As mentioned before, some allowance should be made for system(s) of loading other than gravity. Probably a majority of underground measurements show horizontal forces exceed vertical forces."

"The most accurate instrumentation on existing supports do not relate directly to heading and freestanding conditions, i.e. the most critical time at the most critical location."

"When reworked, this RSR concept could do much to help the less experienced engineering geologist to better equate his prediction of tunneling conditions for the owner, for the AE, for the contractor and for actual tunneling conditions encountered in each instant tunnel. Thus, both as presently conceived and

better yet, in a reworked concept, could serve as a good checklist and tool to each engineering geologist for an instant project. It cannot, without serious legal problems, become a substitute for prudent engineering geological judgment. However, I feel that the RSR is a serious step forward to assist us in the finding of tools to serve to further reduce unforeseen tunneling conditions."

"The proper use of RSR during the planning and design phases of a project would be of the most benefit to the industry. Although the contractors will always be responsible for the prosecution and safety of the work a much better pre-bid evaluation could be made."

"Lumping all parameters into one RSR might tend to oversimplify the problems -- I think the emphasis should be placed on the major parameters (such as Item II-2) and then move to estimates of support using summary charts. The tendency might be for people to classify rock on basis of RSR. I agree with the need for becoming more definitive in the determination of support requirements, and found your work very interesting. Perhaps, in using a single RSR, you could place more emphasis on the parameters goind into the rating, I would like to use already developed rating, along with other parameters, as you've described in your work, and as I outlined in Item II-2."

"Present day methods of evaluating support requirements are not based on reliable standards, but on personal judgment and experience. The reason for this is perhaps due to many uncertainties that are involved in appraising the condition and structural behavior of sub-surface materials. In view of this circumstance, the geologic appraisals have been almost entirely descriptive and in verbal terminology which does not render an explicit workable dimension. Needless to say, tunneling technology, in the geological sense, seriously needs improvement so that engineers, geologists and contractors can communicate on a knowledgable and workable level. The RSR concept is a significant step in that direction. Any new concept of appraising the geologic and tunneling condition of rock should avoid using descriptions that lack dimensions such as highly jointed; thinly bedded; moderately blocky; slightly folded; intesely faulted; etc. A concept, whereby these descriptions are replaced by common standards, should help to establish a basic foundation for geotechnical research in tunneling."

"This can be a step forward if it doesn't become too complicated for the ordinary tunnel contractor."

"An excellent start. Needs to be updated as the significance of this approach is accepted by the industry, and better quantitative records are kept and 'pre' and 'as-constructed' data."

"The changed condition clause in most contracts is a very misused thing. A small error in prediction can be magnified by the contractor. The RSR may

provide more grounds for such a claim. The contractor will still place more supports than instruments show is needed if the specifications are written to allow him to bid such that he profits by oversupporting. One method of doing this is lump sum excavation bid item."

"I'm a bit hesitant to use a combined rating which lumps several parameters. I'd rather use several known parameters separately as a classification. I'm afraid there will be too many changes in the RSR with time."

"The RSR Concept needs to be developed somewhat further so as to exactly pick out the section of rib required. I think the RSR Concept is a good one but the Rib Ratio (RR) technique needs to be improved. In the example of the Donjay Tunnel for instance, Section D requires ribs at 6 and 7 ft., depending on D and B and TBM. Yet this is not shown by the Support Requirement Chart."

"This is the best proposal I have seen to date. I believe it can be used in many cases with good results. It is simple enough so that the average walker and shifter can understand it and put it to use. Too many systems are so technical and/or complicated that an engineer or geologist is required to make use of them."

"I just don't believe it will work."

"I am greatly in favor of developing a better classification system based on rock mechanics -- I am in favor of the proposed scheme of rock structure classification for support prediction provided it is developed in conjunction with other important prediction requirements as: (1) permanent tunnel lining, (2) construction and excavation methods, and (3) special problems and hazards."

"This method has tremendous possibility. I will be very much interested in seeing the final report."

"Generally favorable."

"It is a step in the right direction."

"Contractors may use system more conclusively than is justified in order to obtain contractual advantages."

"Large faults and associated heavy ground zones are major causes of delays in construction, especially where associated with water inflows. To a degree this possibility is considered, but some additional provision for such eventualities based on geologic evidence might be included."

APPENDIX B

NEW CONCEPTS OF GROUND SUPPORT

Research conducted under Contract H0 210038 (Ref. 1) included the investigation of new concepts of ground support which might improve the present state-of-the-art of rapid underground excavation. Sixteen different concepts were studied and subsequently evaluated with respect to the overall tunneling process. By means of an engineering trade-off analysis, each concept was rated as to its potential in improving the art. This Appendix gives a brief synopsis of the previous work with respect to the five most promising candidates plus discussion of several other concepts which are currently being developed by the U. S. Bureau of Mines and their contractors.

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APPENDIX B

NEW CONCEPTS OF GROUND SUPPORT

B.1 INTRODUCTION

"The growing national concern for enhancing and maintaining the quality of the environment in the face of growing resource and urban development demands would be substantially lessened if greatly improved underground-excavation technology were available; i.e., if the real cost of underground excavation were reduced 30 to 50 percent, and if sustained rate of advance were increased 200 to 300 percent in both soft, medium and hard rock."

The above statement is taken from the National Academy of Sciences' report on Rapid Excavation, (10) submitted to the Bureau of Mines in 1968. It defines a goal to be achieved within a period of ten years. The two requirements - reduction in costs and increase in rate of advance - are relative to each other; that is, an increase in rate of advance is tantamount to a reduction in cost. The proportional relationship varies depending on method of excavation (drill and blast or boring machine), type of rock structure and if required, the support system being used. The effect of the support requirement is probably the most crucial element to be considered. To achieve the designated goal, it will be necessary to develop an optimum support system which is defined as "That system which provides safe, efficient and economical ground support with little or no reduction in the potential rate of advance that could be achieved in driving an unsupported tunnel." It must be an

integral part of the overall tunneling process with respect to all components of work and cost.

A new concept could consider or include the use of new materials or techniques; variations of existing methods, and/or possible combinations thereof. Due to large variations in requirements depending on rock structure, tunnel size and method of excavation, no one support system is expected to provide optimum results for all tunnels. The general appraisals made for specific conditions as discussed in the following paragraphs are indicative of concepts which would be applicable to most tunnels considered within the scope of the present research. They may, however, not be applicable to innovative methods of excavation, such as high velocity projectiles or thermal disintegration.

B.2 COMPONENTS OF THE TUNNELING PROCESS

The tunneling process is composed of various subsystems, all of which must be effectively integrated to provide an efficient and continuous operation. These subsystems, which are generally defined as 1) excavation, 2) ground control, 3) logistics, and 4) environmental control, can be evaluated with respect to various applicable cost components such as labor, material and equipment operation. Although each subsystem can be analyzed individually, it is necessary to consider the relative effect of each with respect to the others in final determinations. This is due primarily to the cyclic or sequential nature of tunnel construction. In most instances the tunneling process can be described or evaluated in terms of cost per lineal

foot of tunnel, which reflects the total of individual cost components pertaining to each subsystem involved. Figure B.1 shows the estimated costs for an unsupported (without the ground control subsystem), 20-foot bored tunnel being advanced at the rate of approximately 200 feet per day. It lists the dollar cost per lineal foot of tunnel as well as percent of total cost represented by each component.

Assuming the rock structure for the above example was such as to require continuous support, it would be necessary to add the ground control subsystem to the overall evaluation. This addition will affect all work and cost components, but its principal effect is reflected in increased cost of direct labor and support materials which, in turn, are dependent on type of support being installed. Figure B.2 shows the cost and percentage increase of direct labor and support materials resulting from the necessity of installing conventional support systems at the face. Although the direct labor component reflects additional requirements (logistics, support installations, etc), the major portion of the indicated increase is due to the substantial decrease in daily advance rate occasioned by driving a supported tunnel within the concept of the present state-of-the-art.

The total effect of adding the ground control subsystem to the tunneling process is shown by the cost summary given on Figure B.3. This comparison shows the increase in total costs per lineal foot due to support installation to be 49% to 74% of the basic cost of an unsupported tunnel. These increases, which include consideration of all applicable components

ESTIMATED COST
20' TUNNEL - UNSUPPORTED
MEDIUM HARD ROCK - TBM METHOD
COST PER LINEAL FOOT

COST COMPONENT	ESTIMATED DOLLARS	PERCENT OF TOTAL COST
Direct Labor	$ 48.00	19%
Equipment Operation	26.00	11%
Cutter Costs	40.00	16%
Job M & S	6.00	2%
Support Materials	0.00	0%
Overhead Expense	19.00	8%
Plant & Equipment (Including TBM)	68.00	27%
Profit & Contingency	43.00	17%
TOTALS	$250.00	100%

Figure B.1

COMPARISON
DIRECT LABOR & SUPPORT MATERIAL COST COMPONENTS
UNSUPPORTED VS SUPPORTED TUNNEL

TYPE OF SUPPORT	DIRECT LABOR		SUPPORT MATERIALS COST/L.F.	TOTAL COST DIRECT LABOR & SUPPORT MATERIALS	% OF INCREASE OVER UNSUP. SECTION
	COST/L.F. TUNNEL	% OF INCREASE OVER UNSUP. SECTION			
Unsupported	$ 48	-	$ 0	$ 48	-
Rock Bolts 10' Bolts - 6/ring 5' Spacing	$127	165%	$13	$140	192%
Shotcrete 4" Nominal Thickness Above Springline	$176	267%	$17	$193	302%
Steel Ribs 6 W 20 @ 4' Ctrs.	$132	175%	$45	$177	269%

Figure B.2

COMPARISON OF COST COMPONENTS
20 FT - BORED TUNNEL

COST COMPONENT	UNSUPPORTED	TYPE OF SUPPORT		
		ROCK BOLTS	SHOTCRETE	STEEL RIBS
Direct Labor	$ 48	$127	$176	$132
Equipment Operations	26	34	38	38
Cutter Costs	40	38	38	37
Job M&S	6	8	9	10
Support Materials	0	13	17	45
Overhead Expense	19	29	32	34
Plant & Equipment	68	70	74	74
Profit & Contingency	43	55	58	58
Total Cost/L.F.	$250	$374	$442	$428
Increase Over Unsupported	-	50%	77%	71%

Figure B.3

of the respective tunneling operations, are substantially less than shown by the comparisons on Figure B.2 which treats only labor and materials. They do, however, indicate the large area of improvement which could be achieved by use of a more optimum support system. Similar comparisons could be made with respect to use of the drill and blast method of excavation. The cost of individual components for the drill and blast method would be different, but the relative increases would be of the same order-of-magnitude as indicated for the machine-type of excavation.

All comparisons would relate to respective component costs determined for the potential maximum rate of excavation or advance of an unsupported tunnel. Consequently the optimum support system must be sensitive to possible improvements of underground-excavation technology.

B.3 NEW SUPPORT MATERIALS

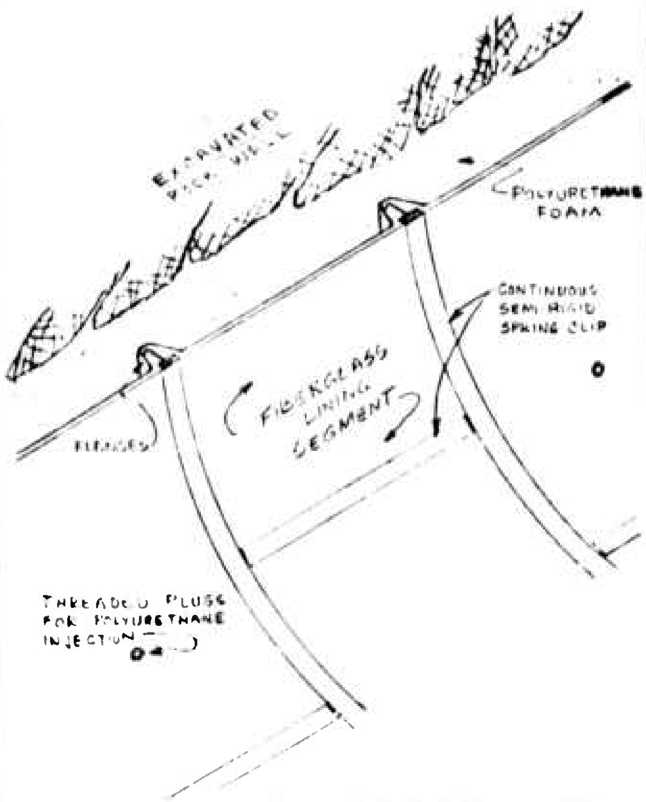
The scope of work included the investigation of new material which might fulfill the requirement for an optimum support system. Although the desired ultimate characteristics and properties of such a material can be defined, the results of the research effort were somewhat less than encouraging. Various new materials such as polymers, fiber glass, epoxies and polyurethane were investigated. Discussions were held with different agencies and organizations involved in the research and development of materials which might fulfill the need. The apparent disadvantages of present prospects outweighs the advantages. With the exception of possible proprietory information, which was not made available to the study

team, it is concluded that within the limits of present-day technology there are no new materials which would immediately meet requirements for an optimum support system. However, it is likely that continued research will provide the ultimate product and that additional improvements in conventional materials such as high-early cement or fiber-impregnated concretes can be expected. Current and recent studies being conducted by the Bureau of Mines and the Department of Transportation, deal specifically with this problem. Examples are "Innovations in Tunnel Support Systems" (11) and "Preliminary Survey of Polymer-Impregnated Rock" (12). The reader is referred to these and similar studies for detailed information pertaining to the present stage of development of new ground support materials. Some of these will be discussed briefly in paragraph B.6.

B.4 NEW CONCEPTS OF GROUND SUPPORT

As used herein a "new concept" is taken as any combination of support materials and method of installation which has not been used extensively in previous tunnel construction. Most involve new techniques or methods as opposed to use of new materials. They relate primarily to tunnels driven with a boring machine which is considered the primary tool for achieving the goal of rapid excavation.

Of the sixteen concepts previously described in Section 7 of Reference 1, the five with the greatest potential will be described. The method of selecting these is given in paragraph B.5. The individual concepts are illustrated on Figures B. 4 through B. 8. A brief critique is given which



No: 3

Title: FIBERGLASS SEGMENTED CYLINDER WITH POLYURETHANE BACKING

Purpose:

Support near face.

AREA OF USE

RSR Range: 20-80

D & B: Face X Behind ___

T.B.M.: Face ___ Behind X

Chance of Success: Fair

Patentability: Good

Comments: One of several possible designs presented.

Originator: Tiedemann

Description: Thin shell segmented lining would be set at face in D & B Tunnel or at tail end of TBM. Polyurethane foam would be injected to fill void between lining and rock, to act as continuous, impervious, blocking. Thickness of web can vary with anticipated rock loads. Design and detail should take advantage of fiberglass properties, light weight, moldability, etc. Concept shown reduces erection time and cost by eliminating bolting. Segments sized as shown can be erected by hand or light weight erector.

Advantages: Provides complete temporary and permanent support within minutes after lining is set. Segments light, easy to erect, no bolting. Polyurethane provides more uniform loading and good resistance to shock.

Disadvantages: High material cost. Low heat resistance. Requires protection during blasting of face.

Figure B.4

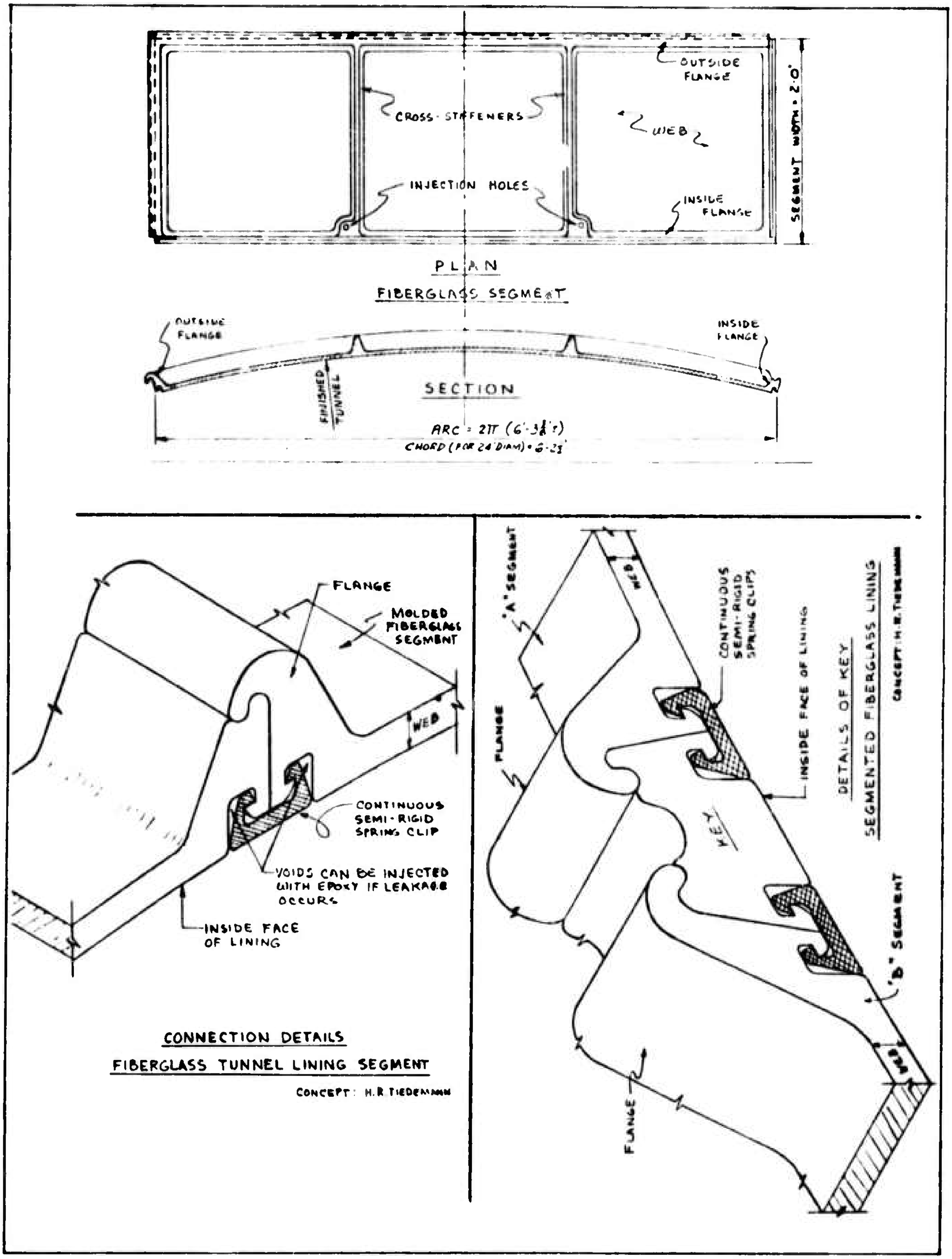
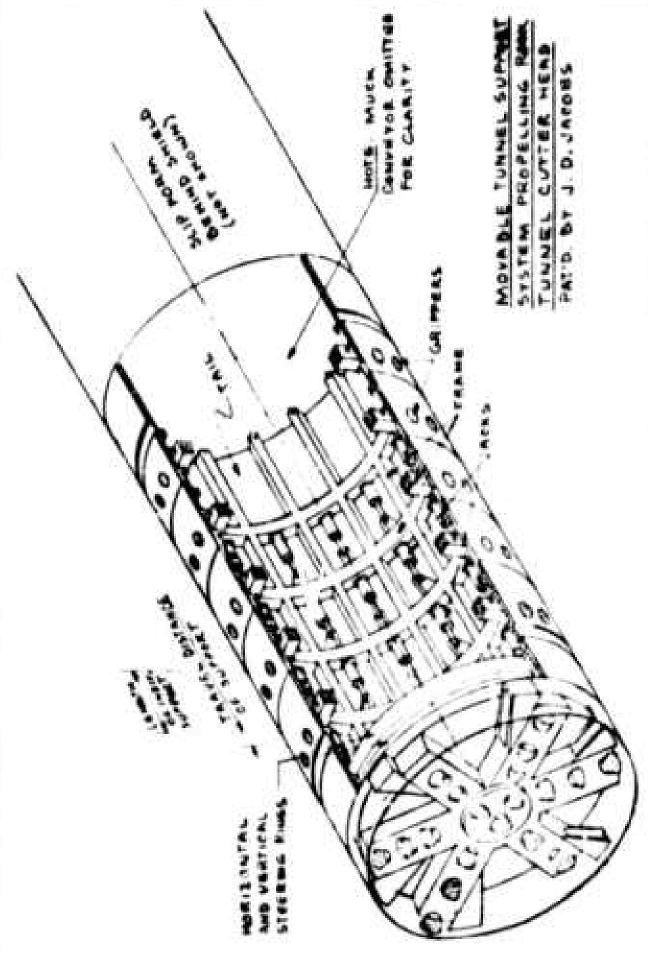


Figure B.4 (continued)

GROUND SUPPORT CONCEPT SUMMARY



No: 9

Title: MOVABLE TUNNEL SUPPORT SYSTEM

Purpose: Support ground temporarily at face.

AREA OF USE

RSR Range: 20-80

D & B: Face - Behind -

T.B.M.: Face X Behind

Chance of Success: Good

Patentability: Already patented.

Comments: Patent by J. D. Jacobs (No. 3, 613, 379)

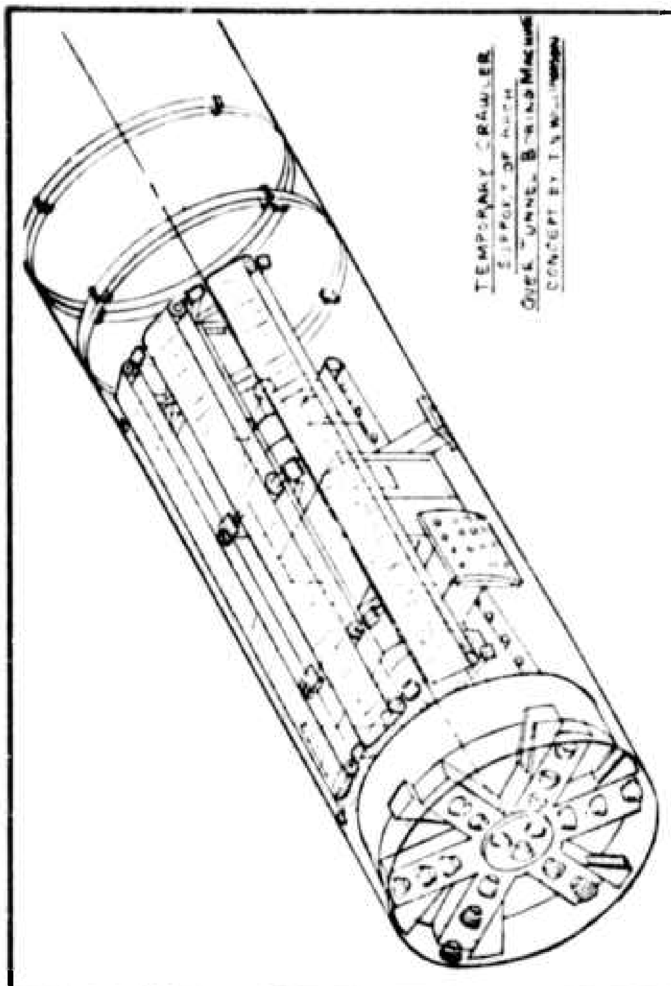
Description: A system of continuous, partly overlapping rings with an appropriate cutter head. Serves the dual function of temporary support at the face, and propulsion of the cutter head. The rings move in small increments, (by use of jacks), one at a time, from front to rear. By use of transverse jacks (not shown) the ring to be moved reduces its diameter slightly and pulls in its grippers. It then moves forward by pushing against the frame system. The other rings maintain a constant pressure against the frame (and in turn the rotating cutter head). These rings are held in position by pressing outward on the rock with multiple small grippers. This machine was designed to be used in conjunction with a slip form behind with continuous reinforcing (concept No. 11), But any suitable support could be erected in the protection of the tail.

Advantages: Provides continuous temporary support. In addition, it provides continuous excavation by eliminating the need to retract and move large sidewall grippers. Thus this type of machine makes possible an optimum system of excavation and support.

Disadvantages:

Figure B.5

GROUND SUPPORT CONCEPT SUMMARY



No: 10

Title: CRAWLER SUPPORT OVER TBM

Purpose: Support ground temporarily at face.

AREA OF USE

RSR Range: 40-80

D & B: Face - Behind -

T.B.M.: Face X Behind

Chance of Success: Good

Patentability: Good

Comments:

Originator: Williamson

Description: Continuous tractor type steel crawlers are mounted, closely spaced, above TBM, running from cutting head to tail end of machine. They will be held in place by hydraulic jacks and be capable of being raised or lowered as required. Crawlers would not be powered.

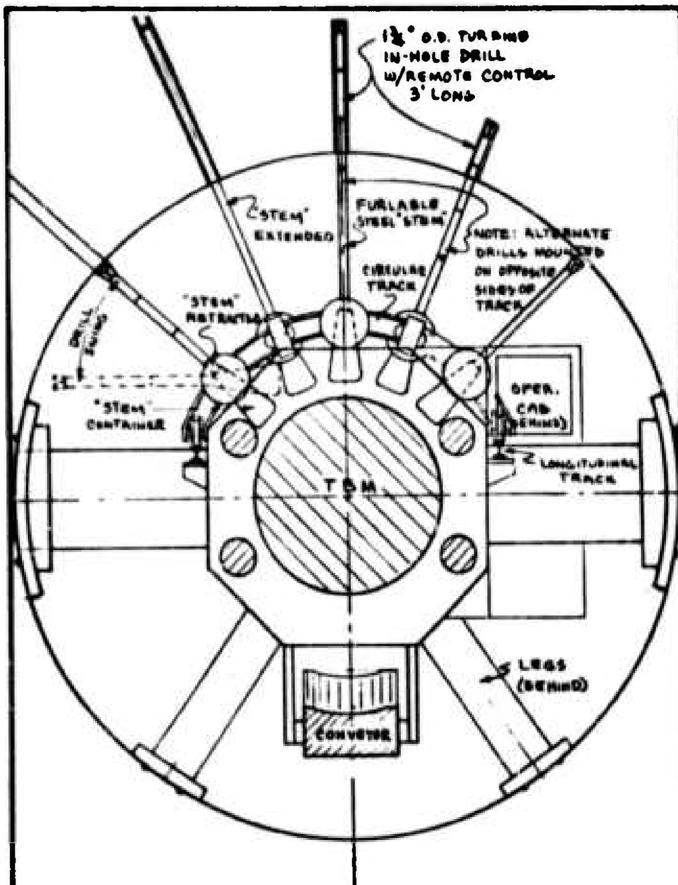
Their function is to hold the rock until other support can be placed behind the TBM.

Advantages: Permits setting of ground support behind machine where there is more room and less interference with excavation. Reduces drag friction of shield over TBM by maintaining point to point contact with rock.

Disadvantages: Small rocks may fall between crawlers. Rock has more time to loosen, which may make load transfer difficult in lower RSR range.

Figure B.6

GROUND SUPPORT CONCEPT SUMMARY



REMOTE CONTROLLED TURBINE DRILLS MOUNTED ON GANG DRILL CARRIAGE TO DRILL HOLES IN ARCH FOR ROCK BOLTS OR POLYMER INJECTION

No: 12

Title: RADIAL GANG DRILL CARRIAGE

Purpose: Drill for rock bolts or polymer injection.

AREA OF USE

RSR Range: 45-80

D & B: Face X Behind ____

T.B.M.: Face X Behind ____

Chance of Success: Fair

Patentability: Fair

Comments: "STEM" - Storable Tubular Extendible Member (Pat'd.) - short turbine drill being developed by Dyna-Drill.

Originator: Wickham

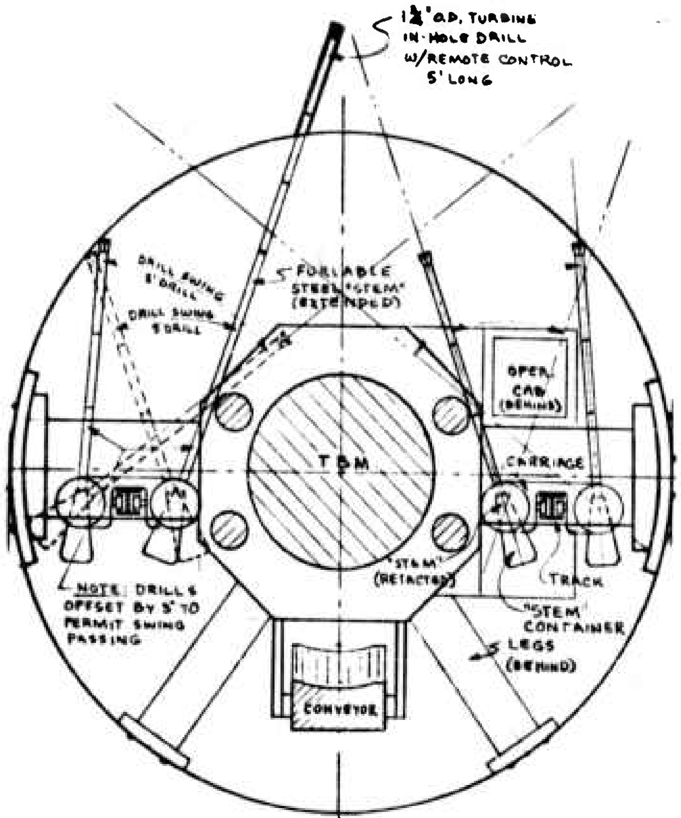
Description: Drills mounted on movable track to drill radial (or near radial) holes for insertion of rock bolts, or polymer injection for rock joint cementation. Short, lightweight, in-hole turbine drills, and strong furlable drill steel are shown, but alternate possible combinations exist.

See 12a for alternate drill set-up utilizing longer drills if shorter drills cannot be developed.

Advantages: Permits rapid gang drilling of holes behind cutter head of TBM not possible with present equipment.

Disadvantages: Much development and testing necessary for drills, furlable drill steel and remote controls.

Figure B.7

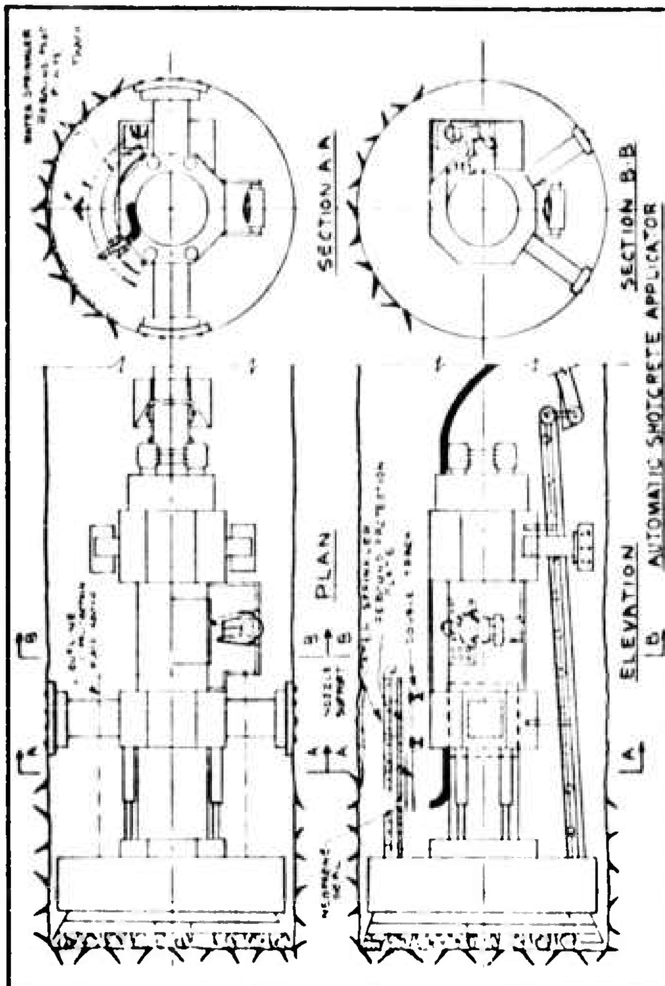


REMOTE CONTROLLED TURBINE DRILLS MOUNTED ON T.B.M. TO DRILL HOLES IN ARCH FOR ROCK BOLTS OR POLYMER INJECTION

Note: Turbine drill lengths shown are maximum for 14' tunnel with T.B.M. as shown. Larger tunnels could accommodate longer drills.

Figure B.7 (continued)

GROUND SUPPORT CONCEPT SUMMARY



No: 13

Title: AUTOMATIC SHOTCRETE APPLICATOR

Purpose: Apply shotcrete over TBM or drill jumbo.

AREA OF USE

RSR Range: 40-80

D & B: Face X Behind

T.B.M.: Face X Behind

Chance of Success: Good

Patentability: Others are working on similar concepts.

Comments:

Originator: Wickham

Description: Applicator would be used on a remote controlled carriage on a circular track mounted above a TBM or drill jumbo. Nozzle would project thru a slot in a steel rebound plate. The slot would have a split neoprene seal. A water sprinkler system would keep rebound plate wet and troughs (not shown) would deposit wet rebound material on muck conveyor.

Advantages: Particularly useful for rock support in lower ranges of RSR values that may not stand unsupported for long.

Disadvantages: Takes up a lot of space - probably could not be used in small (under 14' ft. diameter) tunnels. Dust - fog, etc. associated with shotcrete.

Figure B.8

points out potential advantages and disadvantages as well as general descriptive comments pertinent to each. These and other noted considerations are used in the overall evaluation given in paragraph B. 5. The intent was to show a variety of concepts even though some are obviously beyond the limits of present day technology.

A 14 foot diameter tunnel is used to depict the various concepts described above. It is felt that this is the smallest practical sized tunnel to be considered due to critical space limitations between the tunnel wall and the configuration of present-day boring machines. The feasibility of some concepts would be improved if mechanically compact boring machines could be developed. Also, if considered with respect to larger sized tunnels, which usually provide more working space between the top of the machine and the tunnel arch. The common practice of using sidewall grippers poses restrictions on the use of full circle support placed behind the cutter head. Some of the concepts would not be adaptable to the drill and blast method of excavation due to the cyclic nature of the operation and the effects of blasting. Some concepts were eliminated because they would require and elaborate material handling system to accommodate continuous support installation, or because they would require vastly improved ventilation systems for successful use. These and other underground logistic and environmental problems were considered in the evaluation of these concepts.

B. 5 EVALUATION OF GROUND SUPPORT CONCEPTS

For purposes of evaluation of the original sixteen concepts they were

grouped into four general categories 1) New Materials 2) New Uses of Existing Materials 3) Mechanical Support and 4) Mechanical Placing Concepts. The numerical numbering of the concepts are in accordance with the above rather than as an indication of preference or evaluation. The concepts are compared with respect to eight different parameters or criteria which affect the tunneling process. The parameters are assigned a relative value on basis of an overall evaluation of 100, which, for purposes of this report reflects the optimum system. The individual concepts are rated numerically with respect to each parameter.

Several appraisals using different parameters and values were made before finalizing the matrix shown on Figure B.9. Each concept was evaluated and rated with respect to its potentiality of fulfilling the requirements for an optimum support system (See paragraph B.1). Possible cost or time of development which might be required for a new material or concept was not included as a separate parameter. However, a general appraisal of that criterion was considered in the overall evaluation of concepts with respect to parameter A - Feasibility. For example, if present or emerging technologies indicated a high possibility of success within the next few years, a relative high feasibility rating was assigned to the respective concept; if not, a low rating was used. In addition, evaluations for parameter A included other general aspects of the tunneling process such as practicability, size of crews, etc. Weighted values assigned for parameters B through H were based on applicable comments and features given for each respective concept.

COMPARISON OF SUPPORT CONCEPTS - SHEET 1									
Parameter	Maximum Values	Support Materials Concepts							
		New Materials				New Uses For Existing Materials			
		1 Spray In Place Polymer	2 Steel & Polyure-thane	3 Fiber-glass & Polyure-thane	4 Long Hole Polymers	5 Long Crown Bars	6 Shotcrete Ribs	7 Gunite & Shotcrete	8 Rock Pins
A. Feasibility	20	5	12	10	5	3	15	13	10
B. Safety and Environment	15	5	8	10	6	5	8	6	8
C. Adaptability to Rapid Excava-tion	15	10	8	9	2	1	6	3	4
D. Adaptability to Wide Range of Rock Conditions	10	6	8	8	3	4	8	6	2
E. Proximity of Support to Face	10	8	7	7	3	3	4	3	3
F. Effect on Continuity of Operations	10	6	4	5	3	2	3	2	5
G. Effect on Working Room Near Face	10	1	2	3	2	2	4	4	3
H. Effect on Mater-ial Handling	10	4	2	3	1	1	4	3	4
TOTAL	100	45	51	55	25	21	52	40	39

Figure B.9

COMPARISON OF SUPPORT CONCEPTS - SHEET 2									
		Mechanical Concepts							
		Mechanical Support			Mechanical Placing Concepts				
Parameter	Maximum Values	9 Movable Support	10 Crawler Support	11 Steel Ribbon	12 Gang Drill	13 Shotcrete Applicator	14 Block Laying Machine	15 Corrugated Fiberglass Machine	16 Spring Steel
A. Feasibility	20	16	15	10	12	15	8	2	5
B. Safety and Environment	15	14	12	6	12	12	8	4	3
C. Adaptability to Rapid Excavation	15	13	12	6	9	11	5	3	6
D. Adaptability to Wide Range of Rock Conditions	10	9	7	4	6	8	4	5	3
E. Proximity of Support to Face	10	10	8	6	7	8	4	4	8
F. Effect on Continuity of Operations	10	8	7	5	6	6	4	4	3
G. Effect on Working Room Near Face	10	8	7	5	7	6	3	3	2
H. Effect on Material Handling	10	7	6	6	8	6	2	2	2
TOTAL	100	85	74	48	67	72	38	27	32

Figure B.9 (continued)

These parameters relate to conditions or features usually considered in evaluating tunnel systems.

It is difficult ot make relative comparisons of basically different support systems, especially those of a conceptual nature, where of necessity, many conclusions are based on assumptions. Although concept #1 has been assigned a relative low rating, it has many theoretical advantages over some of the others. If a suitable plastic material should be developed in the near future, the rating for that concept would be significantly increased. Conversely, a mechanical concept with an indicated high rating might have to be downgraded if engineering studies revealed technical flaws. Concept #8, Rock Pins, would probably have a higher rating if its application were considered solely with respect to coal mining operations instead of conventional tunneling. It is realized that this reasoning might apply to all concepts; that is, it is likely that different ratings would be assigned if each were considered individually with respect to a specific tunneling situation. For purposes of this study, however, all concepts have been rated on the basis of present day technologies and requirements for typical civil works tunnels driven through fair to good rock structures.

The optimum system must be capable of providing adequate support for a wide range of rock conditions (RSR values from 19 to 80) which is considered with respect to parameter D. To a certain extent this requirement can be fulfilled by present systems or new concepts which involve the use of existing support materials, i. e. the size and spacing of steel ribs can

be varied, different thicknesses of shotcrete can be applied and rock bolts installed in varying patterns. While steel ribs are adaptable to all RSR values; shotcrete and rock bolts would probably not be used for initial support in tunnels with an RSR value less than 40. It is possible that concepts using steel or fiberglass segments with polyurethane backing could be made adaptable to all rock conditions. This might be accomplished by varying the thickness of the segment webs and increasing the load carrying capacity (density) of the polyurethane when injected behind the segments. Varying the thickness of sprayed-in-place or corrugated fiberglass linings would increase their adaptability to a larger range of rock conditions. In all cases, evaluation of parameter D must include also the consideration of 1) how the system could be installed and 2) possible delay or interference with the overall tunneling process. In this respect, a concept such as Movable Support - No. 9, has an advantage. It provides complete support for all rock conditions with little or no interference of the heading operation. However, it requires the use of other support systems behind the movable shield.

Although eight different parameters were considered in making the evaluation, it is obvious that each has some effect on the others. This is illustrated to a certain degree by the cost comparisons shown on Figures B. 1, B. 2 and B. 3. Figure B. 9 shows that concepts number 9, 10, 13, 12 and 3 (in order of ratings) offer the greatest potential of fulfilling the requirements of an optimum support system in the near future.

The development of new support materials or new techniques of tunnel

excavation could easily alter the ratings shown on the matrix. Comparing maximum parameter values with respective concept ratings gives an indication of potential improvement which might be made in that specific area or feature of the concept. General appraisals can be made by considering the four different categories. "Mechanical Support" concepts appear to be the most likely candidates for improving the art of tunneling at the present time. "Mechanical Placing" concepts are next, with "New Materials" and "New Uses of Existing Materials" following in that order. Even though ratings for new material concepts have been more or less downgraded due to limitations of existing technology, they show greater potential than concepts using existing materials and about the same as mechanical placing concepts.

Although continued improvements can be expected in all categories, it appears that any significant "breakthrough" in tunnel support systems will be in the area of new materials. This is due to the fact that most of the other concepts presently reflect the results of past research and basic improvements which have been made over an extended period of time. Future technology will probably be more in the nature of modification instead of large advances in overall technologies.

B. 6 STATUS OF NEW CONCEPTS DEVELOPMENT

While the new support systems described in paragraph B. 4 are still in the conceptual stage, development work is currently being carried out on previously conceived tunnel and mine support ideas. The use of polymer concrete in thin precast segments is being tested by the U. S. Bureau of

Reclamation and Department of Transportation, among others. Likewise, the U. S. Bureau of Mines has been owrking directly, and through research and development contractors, on several new concepts of ground control. These include shotcrete, plain and wire reinforced, pumpable rock bolts, polymer stabilization of rock, flexible linings, and yielding rock bolts.

B.6.1 Shotcrete

Although shotcrete has been used in Europe for a number of years, its use in the United States has been very limited until recently. It still remains more of an art than a science. IIT Research Institute, under contract to the Bureau of Mines investigated physical properties of shotcrete under controlled simulated field conditions (13). Results show that controlled high early strength shotcrete can be achieved with fast-set agents or Regulated Set Portland Cement; however their use results in a lower ultimate strength. The Regulated Set cement produces higher early strengths than the fast-set agents. The wet and dry mix equipment used in this research produced shotcrete with similar strengths. No significant strength difference was found between 2-inch and 6-inch thick layers, or when placed on vertical planes or overhead. Laboratory tests of wire-filled shotcrete were made at Battelle Northwest Laboratories on specimens obtained using a dry process machine on vertical test panels. A summary of these test results show a slight decrease of compressive strength and increase of tensile strength up to 20 to 32 percent.

B. 6. 2 Pumpable Rock Bolts

A new fully pumpable, fiberglass-roving-reinforced, polymer roof bolt for mine support is being developed by the Bureau of Mines in conjunction with its contractor, the Brookhaven National Laboratory. The bolt consists of three basic components: a polyester resin, a catalyst, and fiberglass roving. The fluid components are mixed just prior to placing and the glass roving is pulled from a spool, through the placement head as the mixture is pumped into the hole. After placement the polymer forms a stiff gel in 2 to 3 minutes and achieves 80% to 90% of its final strength in 5 to 10 minutes (14). In recent field tests at the White Pine Copper Mine in Michigan pull tests showed that the pull out load for a 1-3/8" by 34" long bolt placed in a dry hole was greater than 16,000 pounds, (the tensile strength of the pulling cables). A prototype bolt placing machine to permit automatic remote placement of pumpable bolts is planned for 1974. Besides the safety features of remote placement, other advantages include: placing bolts of any length, placing long bolts in areas of low head room, drilling with flexible shafts (holes need not be straight), and ease of material handling.

B. 6. 3 Polymer Rock Stabilization

It has been recognized for some time that ground support using chemical stabilization by the chemical bonding of weak or poorly cemented rock could have very useful mine and tunneling applications. Recent development of new polymer materials and successful polymer impregnation of concrete prompted the Bureau of Mines to initiate a research effort to study the feasi-

bility of this concept applied to the strengthening of mine structures. A feasibility study and prototype impregnation machine design was conducted by the Eimco Division of Envirotech Corporation (15). Field testing of this support concept is being evaluated and should yield much useful data on this method of ground control.

B. 6. 4 Flexible Linings

Much theoretical and laboratory investigation of support systems incorporating a flexible liner surrounded by a backpacking material has shown that stresses and deformation of the liner can be controlled by proper design. Studies have indicated that the system behavior is controlled by the surrounding backpacking thickness, material modulus, and the thickness and material properties of the liner. For instance: a system with a 2-inch thick backpacking and a modulus ratio of backpacking to the surrounding medium of 1 to 100 is theoretically shown to decrease the stress in the liner by 25 percent, and a 12-inch thickness to decrease the liner stress by 61 percent. Analyses indicate that for a given modulus ratio, an optimum thickness of the backpacking material can be designed to give the desired stress reduction. Therefore, a theoretical advantage of the flexible liner support system is evident.

Large scale field testing by the Bureau of Mines in cooperation with the Kennecott Copper Corporation at Burgin Mine, Utah, verified that the flexible support system design is effective. A test section of 8-foot diameter corrugated aluminum liner, 58 feet long, with 1/4 inch wall thickness, was installed in an underground drift where previous ground support was a serious

problem. After 11 months, the flexible liner concept is accepted as structurally sound, having deflected only about one inch. This contrasts sharply with abandonment, because of continued failure, of an adjacent circular, rigid-arch system installed in the same drift.

B. 6. 5 Yielding Rock Bolts

The yielding rock bolt concept was originally developed in South Africa and has been laboratory tested by the Bureau of Mines and the Lawrence Livermore Laboratory of the University of California. Designed for ground exhibiting excessive displacement, the bolts advantage is yield at a controlled rate. Conventional bolt capacity to yield is limited to the plastic deformation of the steel. Ordinarily, less than the theoretical plastic deformation occurs before breakage or failure of the anchor when high strain rates are encountered. Basically, a smooth-bore die or collar is fitted to standard rock bolts and the yield load is controlled by varying the configuration of the internal bore of the die. Laboratory tests of yieldable bolts indicated dynamic loading produces slightly higher loads (15%) than static loading. The strain hardening effect which increases yield and ultimate strength is partly offset by adiabatic heating of the threads which causes a decrease in strength. Field tests of 250 yieldable rock bolts are now underway by the U. S. Bureau of Mines at the Lucky Friday Mine.

APPENDIX C

USE OF PREDICTION MODEL

HYPOTHETICAL TUNNEL

Contemplated use of the ground support prediction model is illustrated by considering a hypothetical project -- the Donjay Tunnel. The example has been expanded, but is substantially the same as given in Reference 1 (Section 6), and includes findings and results of the present research effort with discussion of potential actual use given in Section 5. RSR determinations and recommended supports have been revised to be consistent with the final prediction model. Reference to figures or sections other than as included in this Appendix pertains to respective numbers in the report.

CONTENTS

APPENDIX C

USE OF PREDICTION MODEL

HYPOTHETICAL TUNNEL

C.1 INTRODUCTION

An important decision in the design and construction of any tunnel is the initial determination as to whether or not ground support will be required and, if so, the type and amount of support system which should be used. This decision is relevant to all phases of planning, design and construction and has a marked influence on ultimate costs. In the pre-construction period, it provides the basis of making comparative evaluations of competitive bids. Tunneling methods or systems to be used during construction are dependent on predictions of support requirements. This is especially true with respect to boring machines which are usually designed for specific conditions. Most claims or litigation pertaining to tunnel work arise from differences between "anticipated" and "actual" support requirements.

Although in-situ testing and as-built geology provide useful, after-the-fact information, the initial decision requires a realistic appraisal or prediction of subsurface conditions and the subsequent correlation of those conditions with appropriate support systems. The RSR method of prediction and use of Support Requirement Charts as proposed in this report would assist in making that decision. The procedure is illustrated by considering a hypothetical project, the Donjay Tunnel. Various steps, type of inform-

ation required, necessary evaluations and other aspects of the problem are discussed in the following paragraphs. An analysis is made which shows comparative economic evaluations of various conventional support systems used in conjunction with either drill and blast or machine method of excavation.

Although the Donjay example relates primarily to civil applications, similar procedures would be followed in the planning of mining operations such as a long haulage or access tunnel. In the latter instance, contractural stipulations, manpower, direct cost, and schedules would probably be treated differently than as discussed herein.

C.2 DONJAY TUNNEL

This example tunnel is a composite simulation of various tunnel sections considered in case history studies. It is proposed to be constructed in one of the Western States; is approximately 16,000 feet long and can be driven either as a modified horseshoe or circular tunnel section at the option of the contractor. See Figure C.1. Other tunnels have been driven through similar formations within the same general area. The general and special conditions, technical specifications and other contract stipulations are typical of most tunnel projects. Construction time is not critical and no liquidated damages are specified. It is assumed that the hypothetical tunnel site has been inspected by the contractor during the pre-bid period. Available cores and other physical features of the work were examined at that time. Although permanent concrete lining is required through-

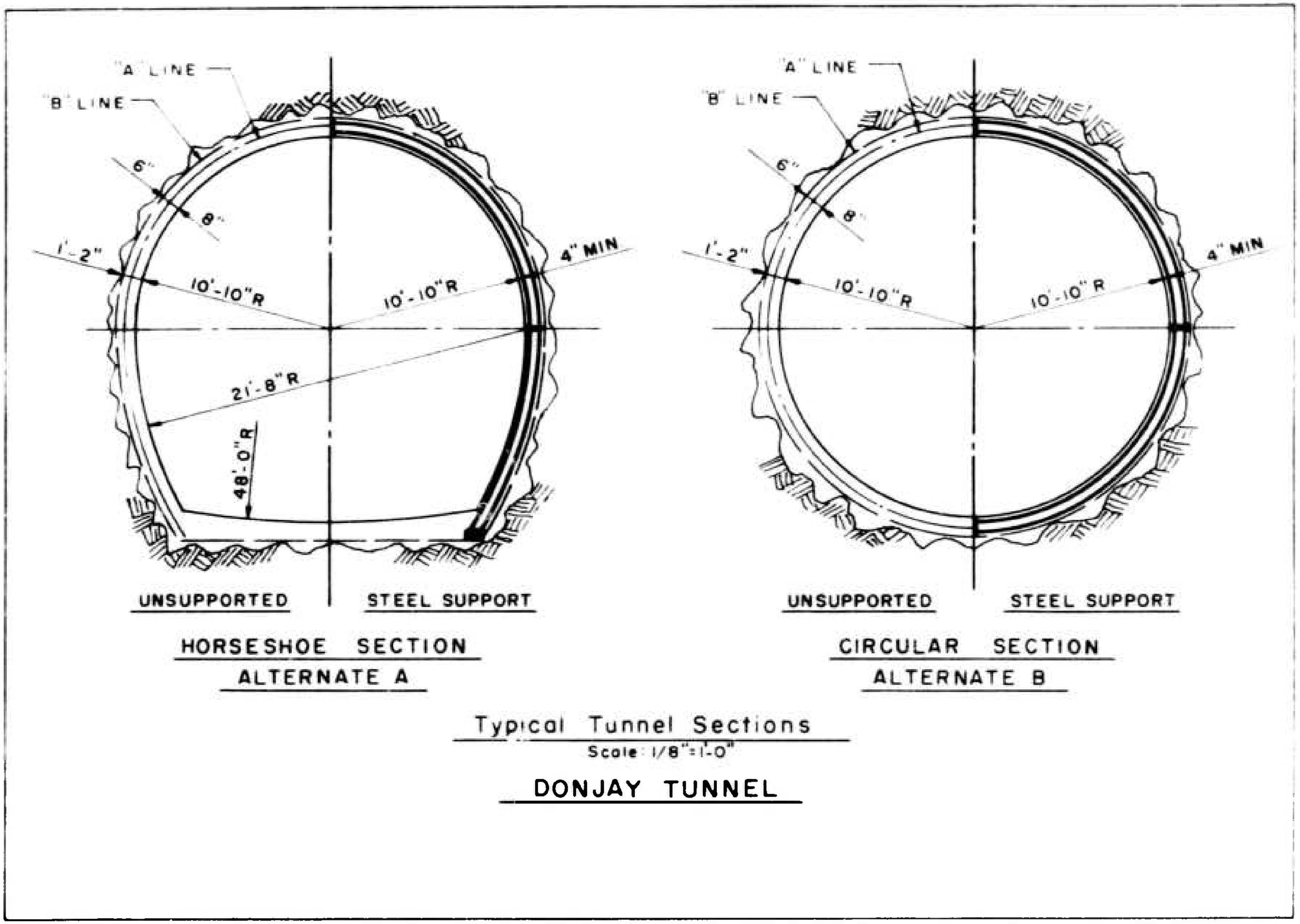

"A" LINE
"B" LINE
6"
8"
1'-2"
10'-10"R
10'-10"R
4" MIN
21'-8"R
48'-0"R
UNSUPPORTED
STEEL SUPPORT
HORSESHOE SECTION
ALTERNATE A
"A" LINE
"B" LINE
6"
8"
1'-2"
10'-10"R
10'-10"R
4" MIN
UNSUPPORTED
STEEL SUPPORT
CIRCULAR SECTION
ALTERNATE B
Typical Tunnel Sections
Scale: 1/8"=1'-0"
DONJAY TUNNEL

Figure C.1

out, this discussion treats only those operations and determinations relating to excavation and initial ground support.

C.3 PRE-CONSTRUCTION GEOLOGY

Geologic data provided with the documents consist of the following:

1. Surface geology
2. Geologic profile along tunnel center line
3. Drillers' Logs of Bore Holes
4. Geologist's report

The specifications include typical disclaimer clauses within the following general context:

"Geologic data is made available only for informational purposes ...."

"Owner disclaims any responsibility for conclusions, interpretations...."

"It is the contractor's sole responsibility...."

"Owner does not represent that geologic data is indicative of conditions to be encountered...."

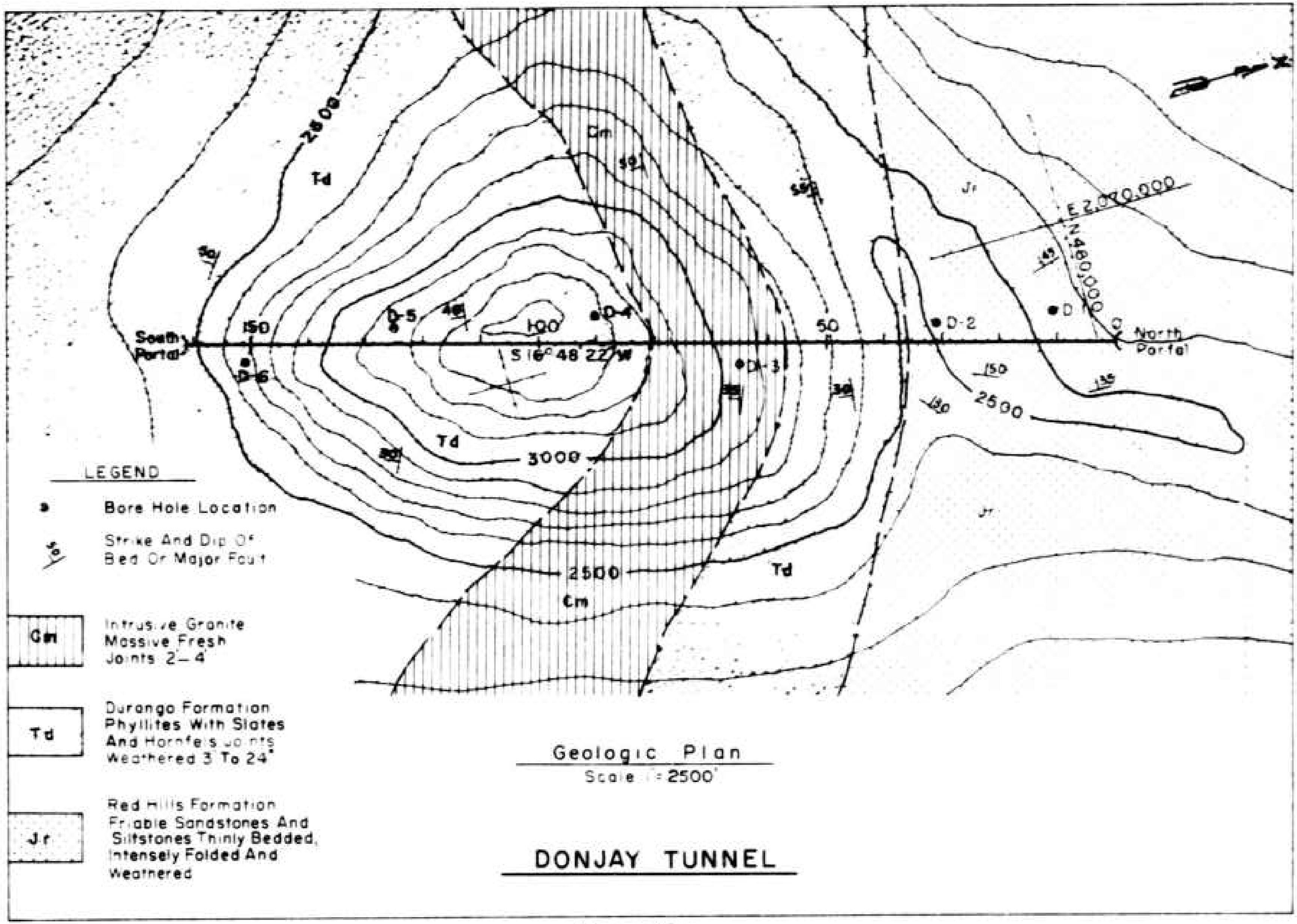
These statements tend to nullify the validity or usefulness of considerable effort and expense which was probably required to document project geology. The owner is in a far better position to conduct geologic investigations and reach conclusions pertaining to subsurface conditions than any potential bidder. This applies to both time and cost considerations. The tunnel will penetrate all rock structures along the alignment

regardless of whether or not they require support and irrespective of who (the owner or contractor) made the initial decision as to support requirements. It is also likely that approximately the same quantity of support will be used in constructing the tunnel regardless of the contractor assigned or the quantity of support indicated in the bid documents. The common goal should be to make the best possible determination of support requirements prior to start of construction rather than to see which party could or might be held responsible in the event subsurface conditions are not exactly as predicted.

The pre-construction geology provided for the Donjay Tunnel is sufficient to make reasonable evaluations of geologic factors which affect support requirements and illustrates the type of information required to determine RSR values.

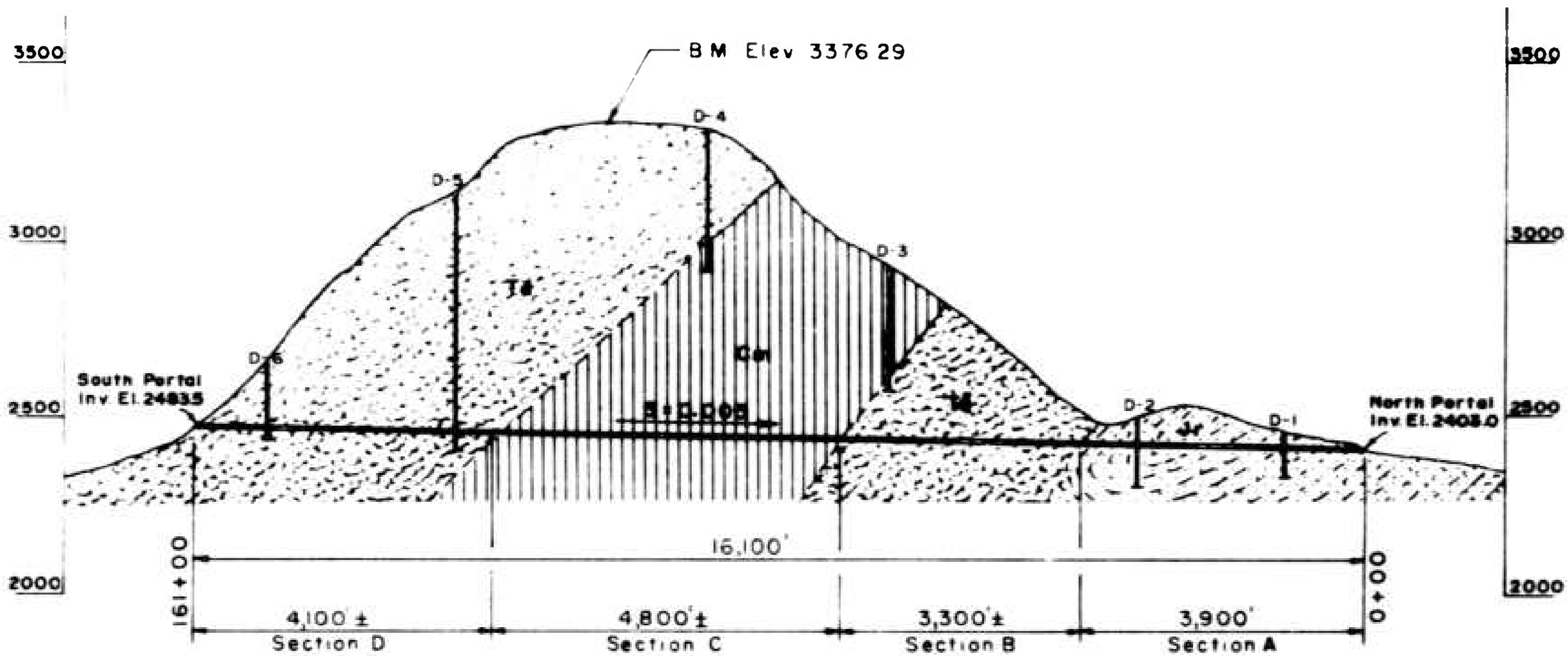
Surface geology is shown on Figure C.2. It gives the essential area topography and shows the approximate extent and general description of geologic formations anticipated along the tunnel line. Surface observations of strike and dip, location of bore holes and other general geologic and engineering information are also noted.

Figure C.3 is the developed geologic profile of the Donjay Tunnel. It shows the owner's, or his geologist's, interpretation and extrapolation of all geologic information developed during the pre-construction investigation. The profile should reflect also, any pertinent data which may have been obtained from study of historical geology and/or records of previous



LEGEND
Bore Hole Location
Strike And Dip Of Bed Or Major Fault
Gm
Intrusive Granite Massive Fresh Joints 2–4'
Td
Durango Formation Phyllites With Slates And Hornfels Joints Weathered 3' To 24'
Jr
Red Hills Formation Friable Sandstones And Siltstones Thinly Bedded, Intensely Folded And Weathered
South Portal
North Portal
S 16° 48' 22" W
E 2,070,000
N 460,000
D-1
D-2
D-3
D-4
D-5
D-6
2800
3000
2500
150
100
50
Geologic Plan
Scale 1" = 2500'
DONJAY TUNNEL

Figure C.2



Pre-Bid Geologic Profile

Scales : 1" = 2500' Horiz.
1" = 500' Vert.

DONJAY TUNNEL

Figure C.3

underground construction. This might consist of attitudes of faults or synclines and anticlines not apparent on the surface. Location and depth of various bore holes are shown. Boundaries between different rock types or formations are projected from the surface to tunnel grade as either a solid or dashed line. A solid line indicating a well defined interface, the dashed line an extrapolation made by the onwer's geologist. Support requirements are usually determined with respect to a geological profile, whether it is provided by the owner or developed by the contractor. Using bore hole information and surface geology given for the Donjay Tunnel, it is likely that all parties would have developed approximately the same profile as given in the documents. This may not have been the case if the geology had been more complicated, i.e. consisted of numerous folds, faults, etc. The profile indicates that the tunnel will penetrate four distinct formations or rock structures. They are identified as Sections A, B, C and D on Figure C.3. Subsequent determinations of RSR values and support requirements are related to those sections of the tunnel.

The logs of various bore holes made during the investigation are shown on Figure C.4. These logs are typical of bore hole information provided for tunnel projects. In some cases Deere's RQD Index might be included along with the % core recovery. A possible addition would be to use a RSR value to describe various rock structures encountered. An important consideration is the location of the bore holes. The geology and types of rock in the area of the Donjay Tunnel are comparatively well defined which

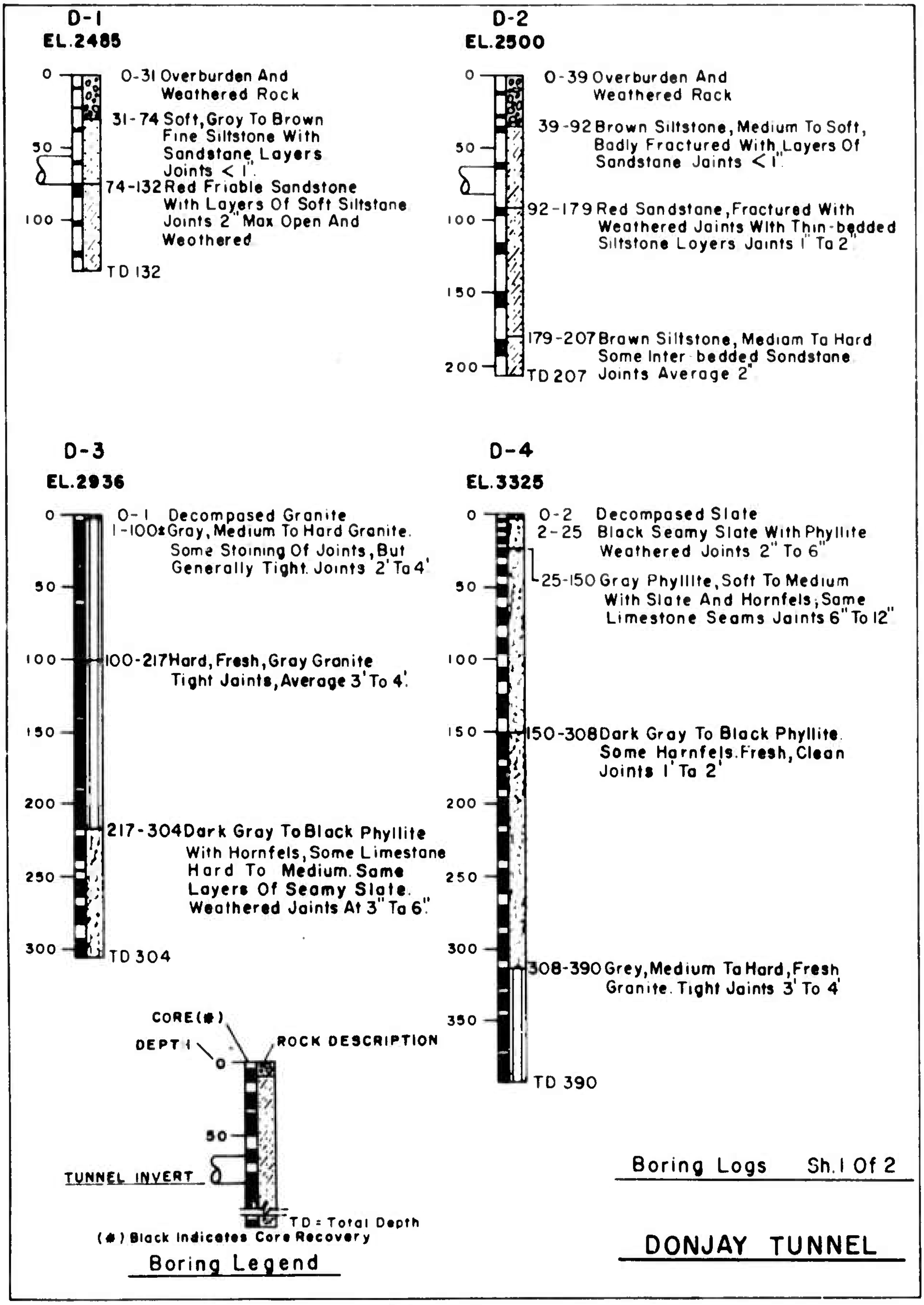

D-1
EL.2485
0-31 Overburden And Weathered Rock
31-74 Soft, Gray To Brown Fine Siltstone With Sandstone Layers Joints < 1"
74-132 Red Friable Sandstone With Layers Of Soft Siltstone Joints 2" Max Open And Weathered
TD 132
D-2
EL.2500
0-39 Overburden And Weathered Rock
39-92 Brown Siltstone, Medium To Soft, Badly Fractured With Layers Of Sandstone Joints < 1"
92-179 Red Sandstone, Fractured With Weathered Joints With Thin-bedded Siltstone Layers Joints 1" To 2"
179-207 Brown Siltstone, Medium To Hard Some Inter-bedded Sandstone Joints Average 2"
TD 207
D-3
EL.2936
0-1 Decomposed Granite
1-100± Gray, Medium To Hard Granite. Some Staining Of Joints, But Generally Tight. Joints 2' To 4'
100-217 Hard, Fresh, Gray Granite Tight Joints, Average 3' To 4'.
217-304 Dark Gray To Black Phyllite With Hornfels, Some Limestone Hard To Medium. Some Layers Of Seamy Slate. Weathered Joints At 3" To 6".
TD 304
D-4
EL.3325
0-2 Decomposed Slate
2-25 Black Seamy Slate With Phyllite Weathered Joints 2" To 6"
25-150 Gray Phyllite, Soft To Medium With Slate And Hornfels, Some Limestone Seams Joints 6" To 12"
150-308 Dark Gray To Black Phyllite. Some Hornfels. Fresh, Clean Joints 1' To 2'
308-390 Grey, Medium To Hard, Fresh Granite. Tight Joints 3' To 4'
TD 390
CORE (*)
DEPTH
ROCK DESCRIPTION
TUNNEL INVERT
TD = Total Depth
(*) Black Indicates Core Recovery
Boring Legend
Boring Logs Sh. 1 Of 2
DONJAY TUNNEL

Figure C.4

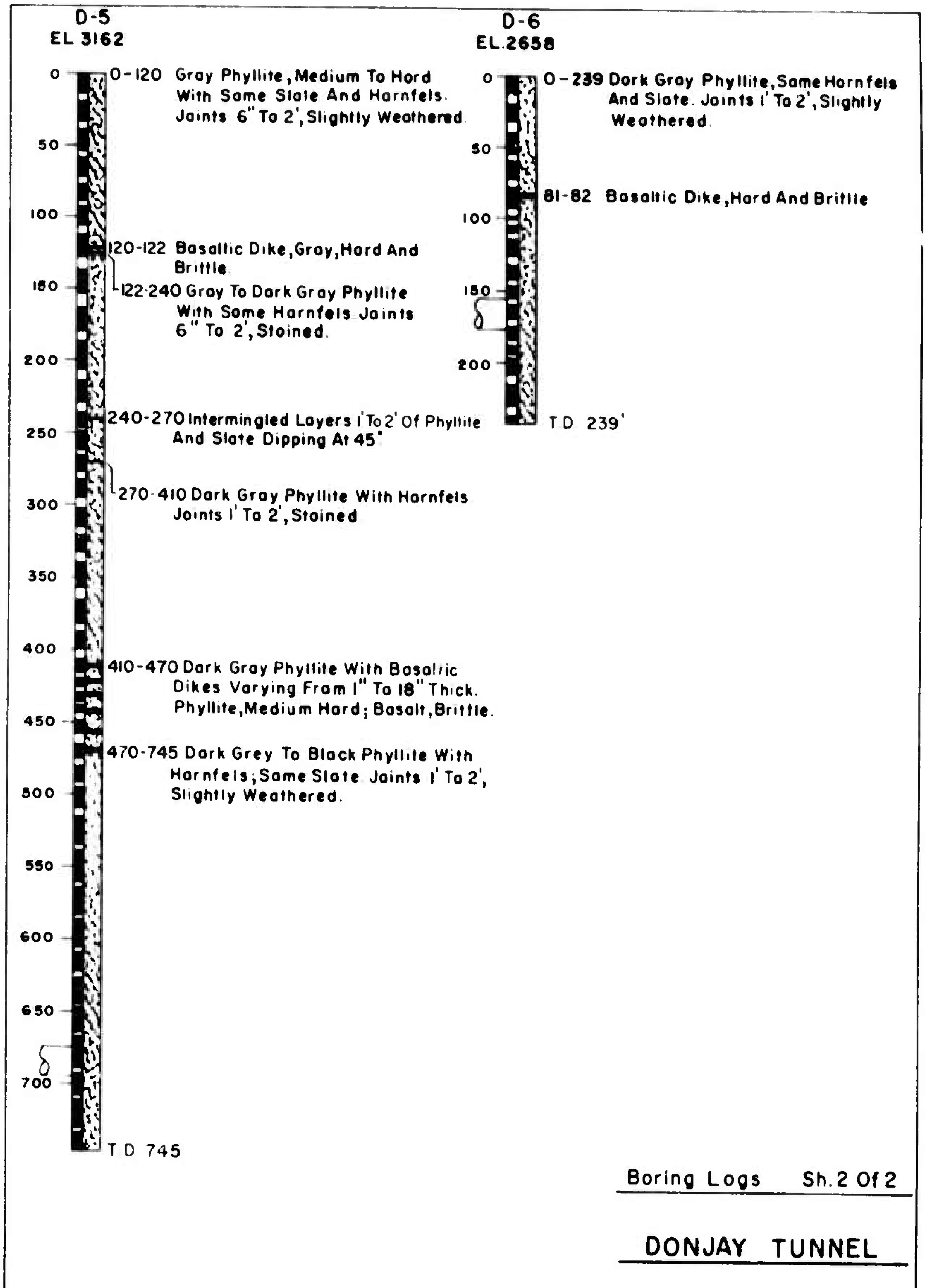


Figure C.4 (continued)

helps in specifying the location of borings. Very often this is not the case. Extensive faulting, erosion and altering of rock may leave transition zones which would be difficult to define even though numerous borings were made at various locations. There is always an elusive point of diminishing returns where the value of information that may be gained from additional borings would not materially add to the accuracy of determining support requirements. Where possible, the boundaries between different rock structures should be defined. This is illustrated by borings D-3, D-4, and D-5 (see Figure C.3) which were made in an attempt to establish the boundaries of two zones of metamorphic rocks and the thick layer of intrusive granite between them. Location of D-5 was approximated by considering the strike and dip of the exposed formations. It was made to verify the projection to grade of the southernmost extent of the intrusion. The fact that it did not encounter the granite even though carried below the tunnel invert, indicated that the boundary lies somewhere to the north of the bore hole. Consequently the projection of this boundary is shown as a dashed line on the profile. The log of D-5 shows the rock at tunnel grade to be more competent than indicated by surface exposures. This information is helpful in determining RSR values for Section D. Boring D-2 was made to define an obvious weakness in the rock structure. Borings D-1 and D-6 depict portal conditions.

Available cores, rock outcrops, road cuts, topographic maps and other data which give indications of subsurface conditions were inspected

and considered during the site visit. No apparent discrepancies were found between conclusions drawn from that inspection and the geologic data presented on the surface geology map, the tunnel profile or driller's logs.

To be complete, the pre-construction geologic survey memorandum should contain a written report or summary, of the findings and interpretations of the geologist who made the investigation and who is familiar with the needs and understanding of tunnel engineers and contractors. In some instances, the desire of the owner to refrain from assuming an implied responsibility for pre-construction geology results in vague or nonconclusive statements. The owner and his engineer representative might spend several years considering a particular project before taking bids. The contractor rarely has more than a few weeks in which he must determine his methods for excavating, supporting and lining the tunnel; consider acquisition of equipment, plant and material and prepare a detailed cost estimate for completing the work. Although a contractor may use a geologist to interpret available prebid geology data, or make an independent appraisal of the site, it is unreasonable to expect him to conduct geologic investigations comparable to that performed by the owner. It should be understood by all concerned that pre-construction geology is not a guarantee as to the actual conditions that might be encountered during tunnel construction. It should, however, be accepted as the best available appraisal of subsurface conditions on which to base project planning and costing. Decisions pertaining to ground support requirements should be made by disciplines directly in-

volved in tunnel construction, not by the courts or related agencies.

A summary of the geology report provided with the Donjay documents is given as Figure C.5. Any such report should include comments pertaining to historical geology, laboratory tests, conditions encountered in previous underground construction, ground water studies or any other data which may have been considered in initial planning or investigation of the tunnel. Special emphasis should be made to identify and define in as much detail as possible those geologic factors and parameters required for a RSR evaluation of the rock structure. (See Figure C.7).

C.4 EVALUATION OF ROCK STRUCTURE RATINGS

RSR values for each of the four Donjay tunnel sections were determined in accordance with procedures discussed in various sections of the final report. Figure C.6 is a tabulation of data considered. The description and occurrence of geologic factors used to define parameters A, B and C are based on information provided in the pre-construction geology. The corresponding values assigned to the different parameters are obtained from Figure C.7. The four tunnel sections encompass a large range of RSR values. Section A, with a rating of 23, is at the lower end of the scale, indicating heavy support requirements. Section C (RSR = 83) is within the range of good competent rock requiring little or no support. Sections B and D with respective rock structure ratings of 44 and 64 will require various types and quantities of support.

The RSR values relate to conventional drill and blast method of

GEOLOGIC REPORT SUMMARY
OF THE PROPOSED DONJAY TUNNEL
(simulated Tunnel Model)

It is anticipated that this tunnel will be most conveniently driven from the north portal as a one-heading operation. This portal area affords more room for a contractor's surface plant and by driving from north to south, the tunnel heading will advance uphill minimizing the pumping of ground water. The amount of time available for construction appears to be sufficient to eliminate the necessity of working from both ends. The description of the rock to be encountered will be given on this basis; however, it will be the contractor's option to drive from either heading.

The first tunnel section adjacent to the north portal, Section A, will probably contain the most severe tunneling conditions to be encountered. This section approximately 3900 ft. in length will be through Jurassic sedimentary deposits known as the Red Hills Formation. This formation consists of intensely folded interbedded layers of siltstones and friable sandstones. This thinly bedded material averages well below 2 inches between joints. The strike and dip vary considerably but average about 30 degrees to 50 degrees in dip, with the strike almost parallel to the tunnel centerline. Borings D-1 and D-2 taken in this formation show RQD Ratings varying between 0 and 30%. The average RSR for this section is estimated at 23. The pumping tests taken on Boring D-2 in the saddle of a slight valley indicate that a flow of 200 gallons/minute and possibly as much as 500 gallons/minute can be expected in this area. Flows of 100 gallons/minute or more can be anticipated anywhere in this formation, especially at the contact with Section B.

Figure C.5

At approximately Sta. 39 + 00 the tunnel will start passing into the Durango Formation. This formation consists of metamorphic rock; principally phyllites with some slates and hornfels and occasional basaltic dikes. (This metamorphic rock will exist in two sections of tunnel, separated by a massive granite intrusion) Section B, between Sta. 39 + 00 and Sta. 72 + 00, consists of thickly layered strata of phyllites and slates. It is generally more seamy than the section at the south portal with joint spacing averaging 3 inches to 6 inches and moderately folded. Although it did not reach tunnel grade Boring D-3, shows a RQD of 60%. The estimated RSR for Section B is 44. The dip of the rock in this section averages 30 degrees to 55 degrees to the south. The strike runs east and west. It is anticipated that water inflow at the face in this area will not exceed 50 to 100 gallons/minute.

From Sta. 72 + 00 to approximately Sta. 120 + 00, Section C, the heading will advance through a hard massive intrusive granite. This rock is tightly jointed with joint spacing varying from 2 to 4 ft. Boring D-3 and Boring D-4 (which penetrates this rock) show RQD of 90% to 100%. The average RSR is 83. Little or no water is expected in this formation, although fracture zones may temporarily yield water.

From approximately Sta. 120 + 00 to the south portal 161 + 00 the tunnel will again pass through the Durango Formation of metamorphic rock. The rock in this area based both on surface outcrops and borings D-5 and D-6 is generally harder, more uniform in texture than the similar rock in Section B. Core RQD range from 65% to 90%. Joint spacing averages 1 to 2 ft. and joints are slightly weathered. The rock consists primarily of phyllites with occasional layers of slate and hornfels. The dip in this area is also 30 degrees to 50 degrees to the south and the strike is generally east to west. The RSR for this section is estimated as 64. Water flows will

Figure C.5 (continued)

be between 50 gpm and 100 gpm and because of steep surface topography, run off is expected to be greater than over Section B.

It is anticipated that Section A will require heavy steel temporary bracing with 50% to 100% timber lagged. Section B will probably require medium support with a minimal amount of lagging. Section C will probably require no support. Section D may require support consisting of light ribs or roof bolts. Use of shotcrete as an alternate support will be permitted. The contractor will have the option of selecting supports with size and/or thicknesses to be approved by the engineer.

Results of laboratory tests of uni-axial compressive strengths:

Boring	Depth	Comp. Str. (psi)
D-1	64'	7,900
	79'	9,500
D-2	91'	8,200
D-3	202'	26,900
	298'	11,000
D-4	252'	13,800
	380'	29,200
D-5	684'	16,700
D-6	161'	14,600

Figure C.5 (continued)

DONJAY TUNNEL
COMPUTATION OF ROCK STRUCTURE RATINGS

	PARAMETER	GEOLOGIC INFORMATION	VALUE
SECTION A	A	Rock Type Sedimentary Intensely Folded	7
	B	Drive $\perp\!\!\perp$ to Axis Dip 30°-50° Joint Spacing $< 2"$	9
	Subtotal		16
	C	Water Inflow-Moderate Joints Badly Weathered	7
	Total RSR Value		23
SECTION B	A	Rock Type - Metamorphic Moderately Folded	13
	B	Drive $\perp$ & with DIP 30°-55° Joint Spacing 3"-6"	16
	Subtotal		29
	C	Water Inflow-Slight Joints Slightly Weathered	15
	Total RSR Value		44
SECTION C	A	Rock Type - Igneous Slightly Folded	22
	B	Drive $\perp$ & with DIP 35°-50° Joint Spacing 2'-4'	38
	Subtotal		60
		Water Inflow - Slight Joints Tight	23
	Total RSR Value		83
SECTION D	A	Rock Type - Metamorphic Moderately Folded	13
	B	Drive $\perp$ & with DIP 30°-50° Joint Spacing 1'-2'	32
	Subtotal		45
	C	Water Inflow - Slight Joints Slightly Weathered	19
	Total RSR Value		64

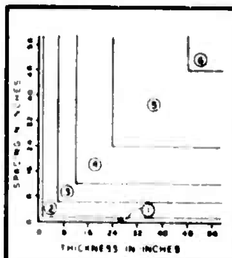
Figure C.6

ROCK STRUCTURE RATING
PARAMETER "A"
GENERAL AREA GEOLOGY

MAX. VALUE 30

BASIC ROCK TYPE	HARD	MED.	SOFT	DECOMP.
IGNEOUS	1	2	3	4
METAMORPHIC	1	2	3	4
SEDIMENTARY	2	3	4	4

	GEOLOGICAL STRUCTURE			
	MASSIVE	SLIGHTLY FAULTED OR FOLDED	MODERATELY FAULTED OR FOLDED	INTENSELY FAULTED OR FOLDED
TYPE 1	30	22	15	9
TYPE 2	27	20	13	8
TYPE 3	24	19	12	7
TYPE 4	19	15	10	9



ROCK STRUCTURE RATING
PARAMETER "B"
JOINT PATTERN
DIRECTION OF DRIVE

MAX. VALUE 45

	STRIKE ⊥ TO AXIS					STRIKE ∥ TO AXIS		
	DIRECTION OF DRIVE					DIRECTION OF DRIVE		
	BOTH	WITH DIP		AGAINST DIP		BOTH		
	DIP OF PROMINENT JOINTS					DIP OF PROMINENT JOINTS		
	FLAT	DIPPING	VERTICAL	DIPPING	VERTICAL	FLAT	DIPPING	VERTICAL
(1) VERY CLOSELY JOINTED	9	11	13	10	12	9	9	7
(2) CLOSELY JOINTED	13	16	19	15	17	14	14	11
(3) MODERATELY JOINTED	23	24	28	18	22	23	23	19
(4) MODERATE TO BLOCKY	30	32	38	25	28	30	28	24
(5) BLOCKY TO MASSIVE	36	39	40	33	35	38	34	29
(6) MASSIVE	40	43	45	37	40	40	39	34

NOTES: Flat 0 - 20°; Dipping 20° - 50°; Vertical 50° - 80°

ROCK STRUCTURE RATING
PARAMETER "C"
GROUND WATER
JOINT CONDITION

MAX. VALUE 25

ANTICIPATED WATER INFLOW (GPM/1000')	SUM OF PARAMETERS A + B					
	13 - 44			45 - 75		
	JOINT CONDITION					
	GOOD	FAIR	POOR	GOOD	FAIR	POOR
NONE	22	19	12	25	22	18
SLIGHT (<200 gpm)	19	15	8	23	19	14
MODERATE (200-1000 gpm)	15	11	7	21	18	12
HEAVY (>1000 gpm)	10	9	8	18	14	10

Joint Condition: Good = Tight or Cemented; Fair = Slightly Weathered or Altered; Poor = Severely Weathered, Altered, or Open

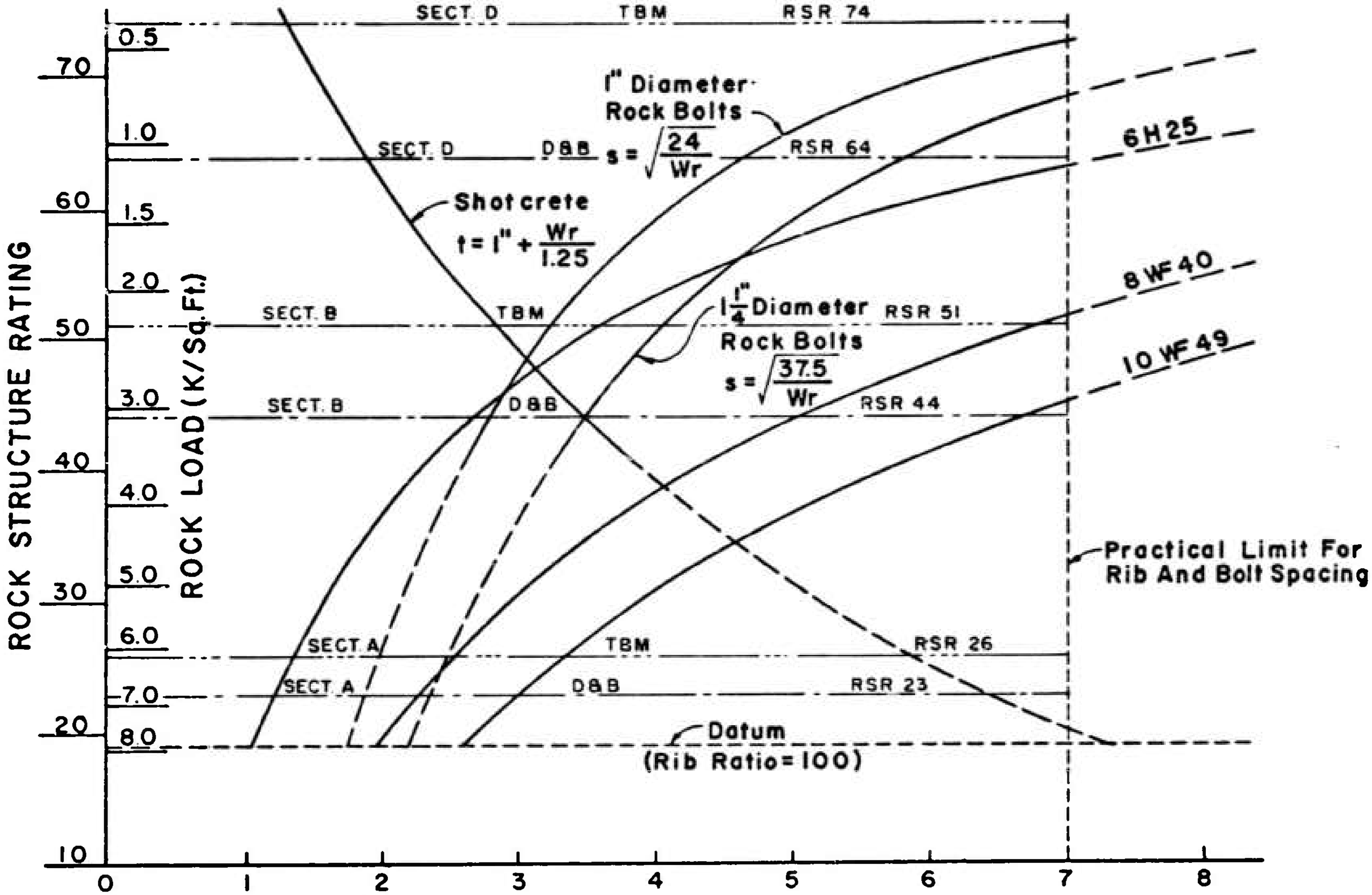
Figure C.7

excavation. It is possible, however, that a boring machine might be used for Donjay. Geologic formations which are anticipated for tunnel sections A, B and D could be readily excavated. Section C (hard granite) is marginal with respect to use of present-day machines. If a contractor chose to use a boring machine (TBM), an approximation of corresponding rock structure ratings could be made as discussed on page 1-19. Using the indicated adjustment factor for a 24-foot diameter tunnel, the RSR values to be considered with respect to a machine operation are as follows:

Section	Basic RSR Value	Adjustment Factor	RSR Value For TBM
A	23	1.15	26
B	44	1.15	51
C	83	1.15	95
D	64	1.15	74

C.5 DETERMINATION OF SUPPORT REQUIREMENTS

Conventional support systems (steel ribs, rock bolts, or shotcrete) that may be appropriate for various support requirements of the Donjay Tunnel can now be identified from a Support Requirement Chart developed for a 24-foot tunnel, which is shown as Figure C.8. Two horizontal lines are shown at the respective RSR values determined for tunnel sections A, B and D. One line represents RSR values for a drill and blast operation, the other, an adjusted RSR value based on use of a TBM. The intersection of these lines with various support curves identifies a support system which would satisfy the support requirement. Only tunnel section C RSR values are above 80, hence support is not considered necessary for either conven-



24' DIAMETER TUNNEL

Figure C.8

tional or machine driven tunnel. Potential support systems are tabulated below:

Donjay Support Requirements

Tunnel Section	Possible Support Systems: Drill and Blast	Possible Support Systems: Machine
A	10 W 49 @ 3'	10 W 49 @ 3 1/2'
B	8 W 40 @ 5' Rock Bolts @ 2 1/2' Shotcrete (4")	8 W 40 @ 6' Rock Bolts @ 3' Shotcrete (3")
C	Unsupported	Unsupported
D	*6H25 @ 6' Rock Bolts @ 4 1/2' Shotcrete (2")	**6H25 @ 7' (for 40%) Rock Bolts @ 6' Shotcrete (1 1/2")

* nominal support
** less than nominal, based on proportion of RR.

The user of a Support Requirement Chart must bear in mind how they were developed and what limitations are imposed. The charts give an average determination of various support systems which would be appropriate for a particular section of tunnel or rock structure. They are not meant to replace the judgement of the man at the heading. Few geologic formations present uniform ground support conditions for any appreciable distance. Consequently, variations of the support system might be required as the tunnel advances. (See paragraph 5.7).

As seen by the above tabulation, it is usually found that several different support systems would be adequate and could be used for those

sections of the tunnel requiring support. Steel ribs can be used in all cases; the use of shotcrete and rock bolts is generally restricted to rock structures having an RSR value greater than 40. Within the intermediate range of fair to good rock structures (RSR values from 40 to 80) the problem always exists as to which system would provide the most optimum solution to the tunneling process. The answer requires a detailed analysis and evaluation of all operations and cost components which are affected by the use of a particular system.

For purposes of this example a tentative appraisal is made to show the general approach and to indicate possible effect on advance rates and costs as occasioned by use of the different support systems, in conjunction with either drill and blast or machine excavation. All situations are analyzed and evaluated in approximately the same manner, consequently comments regarding one system are in general applicable to the others.

C.6 RATE OF ADVANCE

The cost per lineal foot of tunnel, which is an accurate measure of the overall efficiency of the tunneling process, is directly dependent on the daily rate of advance of the tunnel heading. It is determined by considering the relative effect and corresponding time requirements for completing all work operations or subsystems. For conventional drill and blast methods, the subsystems (excavation, ground control, logistics and environmental control) are basically sequential in nature. They can be individually analyzed on the basis of relevant components of work. For example, the work

components or operations pertinent to the drill and blast excavation subsystem are usually identified as follows:

1. Move in and set up drill jumbo
2. Drill blast holes
3. Load powder
4. Blast face and clear smoke time
5. Muck out

Other subsystems can be similarly defined. Each would be evaluated with respect to relative quantities of work involved depending on size of tunnel, rock structure, length of round pulled, etc. Time required to complete each operation is determined by considering the construction capabilities of the particular equipment and labor crew involved. The sum of the separate time requirements is the "cycle time". The maximum or optimum advance per day is obtained by dividing available working hours by cycle time and multiplying by the length of round. This rate is adjusted to allow for lost time and other inefficiencies inherent to tunneling operations so as to arrive at the estimated daily advance rate. This adjustment, or construction efficiency factor, varies with respect to type of operation, length of tunnel, labor regulations and other conditions. Figure C.9 shows a typical format and the determinations used in estimating daily advance rates for the Donjay example tunnel. It lists the major work operations and their respective time requirements. Length of round pulled, cycle times, number of rounds per day and construction efficiency factors used to determine optimum

PROGRESS ESTIMATE FOR DRILL & BLAST TUNNEL WITH CONVENTIONAL GROUND SUPPORT								
TUNNEL SECTION	A	B			C	D		
SUPPORT REQUIREMENT	10 W 49 @ 3'	8 W 40 @ 5'	Rock Bolts @ 2.5'	Shotcrete 4" Thick	No Support	6 H25 @ 6'	Rock Bolts @ 4.5'	Shotcrete 2" Thick
LENGTH OF ROUND PULLED	4'	6'	6'	6'	11'	9'	11'	11'
WORK OPERATION:								
1. Move Jumbo in - set up	0:05	0:05	0:05	0:05	0:05	0:05	0:05	0:05
2. Drill out	0:40	1:05	1:05	1:05	1:30	1:15	1:30	1:30
3. Load and Shoot	0:22	0:23	0:23	0:23	0:25	0:23	0:25	0:25
4. Smoke Time	0:15	0:15	0:15	0:15	0:15	0:15	0:15	0:15
5. Muck out	0:43	1:00	0:55	0:55	1:35	1:20	1:35	1:35
6. Install Supports	0:40	0:38	1:10	0:38	-	0:30	0:32	0:32
7. Miscellaneous	0:10	0:08	0:05	0:05	0:05	0:05	0:05	0:05
Total Cycle Time in Hours	2.91	3.57	3.97	3.45	3.92	3.90	4.45	4.60
No. of Cycles per 22.5 Hr.Da	7.74	6.30	5.67	6.52	5.74	5.77	5.06	4.90
Optimum Advance per Day	31'	38'	34'	39'	63'	52'	56'	54'
Construction Efficiency	85%	85%	87%	85%	90%	86%	87%	86%
Estimated Advance per Day	26'	33'	30'	33'	57'	45'	49'	46'
Reduction in Optimum Rate due to Support Requirements	54%	42%	47%	42%	-	21%	14%	19%
Reduction in Optimum Rate without Operation (6)	40%	32%	26%	28%	-	9%	4%	5%

DONJAY TUNNEL

Figure C.9

and estimated advance rates are shown. Separate analyses have been made for each of the four tunnel sections with respect to applicable support system determined for the drill and blast method of excavation (see tabulation on Page C-23). No supports are required for tunnel Section C.

The tabulation illustrates the overall relative dependency of all conditions and work operations pertinent to the drill and blast method of excavation. The need to provide ground support in different sections of the Donjay Tunnel could reduce the anticipated optimum advance rate (57 feet per day in unsupported Section C) by as much as 54%. This applies also to Section A where the estimated advance rate is 26 feet per day. Percentage reductions for the other sections and support systems are also given. Another evaluation or comparison could be made by eliminating time required to install supports (work operation #6) from respective cycle times. Using the adjusted cycle times, daily advance rates which reflect all operations except the actual installation of support can be determined. A comparison of these rates with the anticipated rate of advance for Section C shows a reduction of approximately 40% (tunnel Section A) as compared to the previously given 54%. This comparison of percentage reduction in daily advance rates; which reflects the extreme conditions of the Donjay Tunnel, shows that a large portion of the reduction is due to conditions dictated by the inherent properties of the rock structure as opposed to the actual installation of supports. It is obvious, however, that all operations and conditions are dependent on each other. For instance, it would not be necessary to use a

PROGRESS ESTIMATE FOR TBM TUNNEL WITH CONVENTIONAL GROUND SUPPORT								
TUNNEL SECTION	A	B			C	D		
SUPPORT	10 W 49 @ 3-1/2'	8 W 40 @ 6'	Rock Bolts 3'x3'	Shotcrete 3" Thick	No Support	6H25 @ 7' (for 40%)	Rock Bolts 6'x6'	Shotcrete 1-1/2" Th.
Distance traveled before setting support	3.5'	6'	6'	6'	-	7'	6'	7'
Basic Progress (60% of Max. Penetration Rate)	12'/Hr	9'/Hr	9'/Hr	9'/Hr	2.5'/Hr	6'/Hr	6'/Hr	6'/Hr
Cycle Time (Hours)								
A. Setting Support	0.80	0.60	1.75 *3	0.85 *2	-	0.50	1.10 *4	0.60
B. Interference Factor	1.00	0.50	0.50	1.00	-	0.25	0.25	0.50
C. Support Time in Cycle (AxB)	0.80	0.30	0.88	0.85	-	0.13	0.28	0.30
D. Travel at Basic Rate	0.30	0.61	0.67	0.67	-	1.17	1.00	1.17
E. Total Cycle Time (C+D) or A*1	1.10	0.91	1.75 *1	1.85	-	1.30	1.28	1.47
No. of cycles per 22.5 hour day	20.5	24.7	12.9	14.8	-	17.3	17.6	15.3
Total Advance (Ft/Day)	72	135	77	89	56	121	105	107
% of Basic Rate	25%	63%	36%	40%	94%	84%	73%	75%
% of Max. Pen. Rate	15%	38%	21%	24%	56%	50%	44%	45%
Total Crew Size	114	111	123	117	84	111	111	108

*1 Use (A) time for setting support as total cycle time if it is greater than (C+D)
*2 Arch only. Additional shotcrete gun and crew required for invert
*3 Based on five roof bolt crews
*4 Based on two roof bolt crews

DONJAY TUNNEL

Figure C.10

four foot round for Section A if the rock structure did not require support. This interdependency is most pronounced for the drill and blast method wherein all operations are sequential in nature. It has less effect for machine methods and possibly could be eliminated by development of new technologies or concepts.

Following the same general procedure as outlined on Figure C.9, estimates were made of daily advance rates that may be achieved by use of a TBM. Results are shown on Figure C.10. Different operations are considered in analyzing the machine method of excavation. Advance rates for boring machines are usually determined by first considering the maximum penetration rate; which is dependent on machine design and rock properties, and then reducing that rate in proportion to anticipated interference or delays caused by other operations.

C.7 COST EVALUATIONS

Having estimated daily advance rates for the various tunneling situations it is now possible to determine applicable costs per lineal foot of tunnel. Costs, such as labor, equipment operation and depreciation, supervision, overhead, etc. are directly related to time requirements. Job materials, small tools and supplies and permanent materials are based on actual requirements or quantities used to complete the work. Plant installations or requirements and contractor's mark-up (profit and contingency) are dependent on the particular project being considered. The same general costing procedure is followed in all cases, regardless of whether or not

the work is to be accomplished by conventional drill and blast methods or by use of a boring machine.

As mentioned previously, this report does not include the large amount of detail and calculations which would be required to prepare an actual cost estimate. It does, however, present results which reflect typical procedures used in estimating tunnel costs and shows comparative evaluations of different support systems and excavation methods.

The cost components most affected by support installations are direct labor and support materials. Labor costs are directly proportional to the size of crews and daily advance rate. Typical size of crews (excluding supervision and overhead) for the Donjay Tunnel would vary between 112 and 121 men per day (three shifts) for a drill and blast operation. Assuming an average hourly labor rate of $10.50 (1973 base) in conjunction with the respective daily advance rates given on Figure C.9 it is possible to determine the direct labor cost per foot of tunnel.

Cost of support material is determined by extending the applicable unit price against the quantity of support material required for one foot of tunnel. Quantity of material for each support system is based on respective requirements such as rib size and spacing, thickness of shotcrete, and rock bolt pattern.

Other components of costs such as job materials and supplies, equipment operation (fuel, lube repairs, etc.) overhead and general expenses, plant and equipment write-off and mark-up have been determined on the basis

of total requirements for constructing the Donjay example tunnel.

Estimated cost for a drill and blast operation is shown on Figure C.11. It gives reasonable appraisal of costs per foot of tunnel as occasioned by use of the respective support system.

Costs per lineal foot of supported tunnel range from 120% to 230% of the cost of the unsupported Section C. This is approximately the same differential as indicated by the analysis of daily advance rates.

On the basis of this evaluation, the most efficient (least costly) conventional support system to be used for tunnel sections B and D would be shotcrete. Section C is unsupported. Due to low predicted rock structure rating for Section A, only steel ribs were considered. The other systems would probably not be competitive. The cost per foot of tunnel for the respective components gives an indication of their relative effect on the overall tunneling operation.

Figure C.12 shows results of a similar evaluation made by considering conventional support systems with the machine method of excavation for the Donjay Tunnel. Costs were determined in the same manner as those for the drill and blast method. Daily advances and crew sizes considered in the evaluation are shown on Figure C.10. Comparing total cost per lineal foot of tunnel as shown for corresponding tunnel sections on Figures C.11 and C.12 shows lower costs for the machine methods for Sections A, B and D. This could be expected due to greater daily advance rate of the TBM. The higher "machine" cost for Section C is due to the fact that hard massive granite

COST SUMMARY - DRILL & BLAST TUNNEL - CONVENTIONAL SUPPORTS							
TUNNEL SECTION & SUPPORT REQUIREMENTS	DIRECT LABOR	JOB MATERIALS AND SUPPLIES	SUPPORT MATERIALS	EQUIPMENT OPERATION	TOTAL DIRECT COSTS	OVERHEAD P&E AND MARKUP	ESTIMATED BID PRICE PER L.F. TUNNEL
<u>SECTION A</u>							
10 W 49 (@ 3')	$362	$48	$182	$37	$629	$333	$962
<u>SECTION B</u>							
8 W 40 (@ 5')	284	45	102	33	464	285	749
Rock Bolts (@ 2-1/2')	337	51	89	34	511	285	796
Shotcrete (4")	299	41	33	35	408	235	643
<u>SECTION C</u>							
Unsupported	164	36	-	28	228	192	420
<u>SECTION D</u>							
6 W 25 (@ 6')	208	39	64	30	341	219	560
Rock Bolts (@ 4-1/2')	207	39	25	30	301	204	505
Shotcrete (2")	215	38	19	31	303	192	495

Figure C.11

COST SUMMARY - TBM TUNNEL - CONVENTIONAL SUPPORTS								
TUNNEL SECTION & SUPPORT REQUIREMENTS	DIRECT LABOR	MATERIALS		EQUIPMENT OPERATION		TOTAL DIRECT COSTS	OVERHEAD P&E AND MARKUP	ESTIMATED BID PRICE PER L.F. TUNNEL
		SMALL TOOLS	SUPPORT MATERIALS	GENERAL	CUTTER COSTS			
<u>SECTION A</u>								
10 W 49 (@ 3-1/2')	$132	$4	$184	$25	$ 22	$367	$312	$679
<u>SECTION B</u>								
8 W 40 (@ 6')	68	2	94	23	30	217	265	482
Rock Bolts (3'x3')	133	4	55	23	30	245	270	515
Shotcrete (3")	110	3	28	26	30	197	258	455
<u>SECTION C</u>								
Unsupported	125	3	-	70	147	345	306	651
<u>SECTION D</u>								
6 H 25 (@ 7' for 40%)	77	2	30	27	48	184	260	444
Rock Bolts (6'x6')	88	2	14	27	48	179	248	427
Shotcrete (1-1/2")	85	2	14	28	48	177	248	425

Figure C.12

(rock encountered in Section C) cannot be economically cut with present day boring machines. The relative position of different support systems with respect to total cost are about the same for both methods of excavation.

On the basis of the above evaluations predicted ground support for the Donjay Tunnel would be as follows:

Tunnel Section	Drill and Blast	TBM
A	10 W 49 @ 3' centers	10 W 49 @ 3 1/2' centers
B	4" shotcrete	3" shotcrete
C	Unsupported	Unsupported
D	2" shotcrete	1-1/2" shotcrete

APPENDIX D

ROCK CLASSIFICATION

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It has been said that the classification of rock as a structural material is not a simple problem (1, pg 466). Classifications are made in order to place things in their natural relations so far as possible and to allow their systematic study. Of course, in actuality sharp demarcations are not possible between artificial degrees of classification. Classification occupies a central position in nearly all sciences, therefore, it is well to consider this in some detail. Whether it has become necessary, or simply convenient, there is a general feeling shared by all workers in science fields that things or objects belong to "classes". Terminology of classification uses terms-definition, correlation, description, and quantitizing such that "divisions" between classes or objects may be made. Perhaps the emphasis for classification is because the language of everyday conversation is filled with vagueness, ambiguity, and replete with inaccuracy (even technical treatises are not always much better).

When the science worker states that it is the business of science to gather the facts and then to classify them, we do not have a clear or adequate account of the situation. First, some manner of classification is involved in determining what facts should be gathered. Obviously, there are few rules

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1) Obert, Leonard, and W.I. Duvall Rock Mechanics and the Design of Structures in Rock. John Wiley, Publ., 1967, 650 pg.

for classification in an informal system of logic. Rigorous pursuit of formal rules would define a "natural" and an "artificial" system of classification (2, Chapter 12). One of the founders of modern methods was Carl Linnaeus (1707-1778), the Swedish naturalist who established the modern system of scientific classification nomenclature - briefly, as order, genera and species. It will be noted that although his original format has undergone revision, its basic outline survives. It is beyond the scope of this Appendix to cover this entire subject but it is concluded by noting that NO classification is theoretically perfect under exact rules of logic. Even such highly structured sciences as botany and chemistry have inadequacies when examined completely.

Since rock classifications are central to this research, it is necessary to briefly review rock classifications (3). All of the previous discussion on formal logic of classification is germane to the history of rock classification. Very early in the development of the subject it was appreciated that there were three great, sharply contrasted genetic rock groups. In modern times, systems of igneous rock classifications were not readily accepted until the Rosenbusch classification (1873 and 1877) and is referred to as the Rosenbusch model classification. It is noted that in the next 50 years over a dozen new rock classification schemes or modifications were proposed.

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2) Cohen, M.R. and Ernest Nagel. An Introduction to Logic and the Scientific Method. Harcourt Brace and Company, 1939, 467 pg

3) Travis, R.B. Classification of Rocks. Quarterly, Colorado School of Mines, v. 50, No. 1, January 1955, 98 pg

Of all these, Johannsen (4) probably submitted the most highly structured system. His review of the general subject is as applicable today as then with the following quotation from his introduction.

> "It is with considerable hesitation that the writer introduce a new classification of igneous rocks. He knows that he who adds a single term to an already overburdened vocabulary is looked upon with disfavor, while he who brings in many has hearty objurgations heaped upon him; yet he hopes, as others who have gone this way before him have hoped, by fixing definite boundary lines beyond which the different families cannot pass, to eliminate the multiplication of rock names which differ in no essential particular from previous described types. It is being recognized more and more, that there is need for three classifications of igneous rocks. One must be for field use, another must be chemical, and the third must be mineralogical."

Johannsen further went on to note that all rock classification systems fail in their lack of quantitative element. The reader may recall that Johannsen's three volume work on rock classification was published in 1931.

The geologist should note that his field is highly oriented toward classification with every subject - from rock to faults, folds, cleavage, joints, and mineralogy, all too numerous for discussion herein, subject to detailed classification. Further noted is that none of these classifications are acceptable to all with discussion continuous to this day.

One of the first engineering uses for rock properties (and indirectly rock classification) was obtained by the Watertown Arsenal and reported during the period 1882 to 1913 (5, pg 393-401). This effort terminated at the

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4) Johannsen, Albert. Suggestions for a Quantitative Mineralogical Classification of Igneous Rocks. Journal of Geology, v. 25, No. 1 Jan-Feb 1917, pg 63-97

5) Watertown Arsenal. Report of the Test of Metals and Other Materials for Industrial Purposes at Watertown Arsenal, Mass. Ordinance Dept. U.S. Army, 1894, pg 322-418

beginning of World War I when the National Bureau of Standards, U.S. Geological Survey, and the Bureau of Mines efforts in rock testing were redirected into avenues which have been followed to the present. This early effort, however, produced results which are widely quoted today in most Civil Engineering handbooks for properties of building stone (6). Although the methods, the testing, and the equipment for these early results would probably not be acceptable today, they are nevertheless widely quoted.

Mitchell in 1917 (7) noted that the need for an accurate rock classification system for engineering work is not always appreciated by engineers and contractors (this is perhaps one of the first published remarks on the subject). Shortly after, Smith (8) and Pirsson (9) elaborated on rock classification for engineering. They noted that technical rock classifications are too clumsy for field use; a good classification will have to include terms used both by geologists and engineers; it must be recognized that all dispute cannot be resolved; and the classification should have regard for the material itself.

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6) Cross, Hardy, and P.J. Brennan. Masonary and Plain Concrete. Chapter 23, pg 23-01 to 23-86, in Abbett, R.W. American Civil Engineering Practice. John Wiley Publ., 3 v., 1957

7) Mitchell, G.J. The Need of Accurate Rock Classification in Engineering Contracts. Economic Geology, v. 12, No. 3, April-May 1917, pg 281

8) Smith, W.D. Rock Classification for Engineering. Economic Geology, v. 14, No. 2, March-April 1919, pg 180-183

9) Pirsson, L.W. Rock Classification for Engineering. Economic Geology, v. 14, No. 3, May 1919, pg 264-266

The Department of Agriculture, then containing the Bureau of Public Roads, was early concerned with rock classification for road building (10). This monumental work was summarized in 1953 with results from over 13,000 rock samples (11). It is illustrative that the final results showed little emphasis on definition of rock and only five "important" physical properties for road building - bulk specific gravity, absorption, abrasion loss, hardness, and toughness. Test methods were developed for each of these properties. The lesson learned is that in the final analysis simple terms and methods to assist the engineer are most desirable.

These few examples illustrate that interest in rock classification for reasons other than science have existed for over half a century. They also show that early results have become influential even though the methods, techniques, and procedures would be of doubtful acceptance today. One cannot dismiss such empirical classification as Friedrich Mohs' (1773-1839) scale of hardness which appears acceptable after over 150 years of use.

It is of further note that many similar simple classifications have been proposed for a host of mining conditions covering everything from rock breakage to drillability. (12, 13, 14, 15)

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10) Lord, E.C.E. Examination and Classification of Rocks for Road Building, Including Physical Properties of Rock with Reference to Mineral, Composition and Structure. Dept. of Agruculture, Bulletin 31, 1908, 29 pg

11) Woolf, D.O. Results of Physical Tests of Road-Building Aggregate (to January 1, 1951). Bureau of Public Roads, Dept. of Commerce, 1953, 225 pg

12) Gyss, E.E. and H.G. Davis. The Hardness and Toughness of Rock. Mining and Metallurgy, v. 8, No. 246, June 1927, pg 261-265

13) Steidle, E. Some Practical and Theoretical Aspects of the Burn Cut. Joy Manufacturing Company, Oliver Bldg. Pittsburgh, Pa., 1951, 14 pg

14) Goodrich, R.H. Rock Classification Tests. Joy Manufacturing Company, Claremont, New Hampshire, 1955, 26 pg

15) White, Christopher. A Rock Drillability Index. Quarterly, Colorado School of Mines, v. 64, No. 2, April 1969

The published literature concerning systematic classifications for mining methods began about 1915. Generally the pure classification of mining methods is of academic interest. Warner (16) considered that the selection of a mining method was a function of internal factors, or those directly associated with the orebody, external factors, or those related to the orebody, and economic factors of the mining operation. Warner noted that some factors influenced the mining process while others affected only the details, but ultimately all factors must be considered. Harley (17) noted that classification of rock conditions for mining purposes will vary with requirements of management, the miner, and the geologist.

The greatest problem in the selection of an underground excavation method is the relationship between geologic conditions and the excavation method. The mining industry's approach along this line has been that each mine is an individual problem. The method of King (18) at the Climax mine in Colorado is typical of such work and is summarized as follows: From a

16) Warner, R.K. Selection of a Mining System. American Institute of Mining and Metall., Trans., v 109, 1934, pg 11-24

17) Harley, G.T. Proposed Ground Classification for Mining Purposes. Eng. and Mining Journal, v. 122, No. 10, September 4, 1926, pg 368-372, and No. 11, September 11, 1926, pg 413-416

18) King, R.V. A Study of Geologic Factors at Climax in Relation to Mining and Block Caving. American Institute of Mining and Metall., Trans., v. 163, 1945, pg 145-155

detailed examination of all mine workings, diamond drill cores, and a careful study of all geologic mapping and drill logs, observed geologic factors are correlated with the behavior of the rock in the stopes being caved. The result is a relative comparison between rock characteristics by recording quantitatively the intensity of fracturing and qualitatively the hardness of the rock, extent of mineralization, weathering, decomposition, disintegration, and oxidation. These data resulted in four classes of rock ranging from strong to weak for which mining methods could be developed. Presently, a modified scheme partially based on this early work is used as a basis for block caving and is known as the "Cavability Index". The index has a range of 1 to 10.

Clark (19) gathered geologic data from 52 mines using 8 mining methods. Clark selected the following seven geologic factors as important in the selection of a mining method: (1) structural type of orebody, (2) dimension or geometry, (3) type of country rock, (4) extent of faulting, folding, and fracturing, (5) alteration of ore and country rock, (6) type of mineralization, and (7) summary of geologic factors. Clark stated that the immediate problem is to interpret physical characteristics of mineral deposits in terms of geologic conditions; but these are the most difficult to properly evaluate.

A similar review of the literature of tunneling shows that no distinctive

19) Clark, G.B. Relationship of Geology to Underground Mining Methods. Mining Engineering (AIME), v. 6, No. 8, August 1954, pg 812-816

excavation-support correlation has been proposed which is based on an engineering scheme of rock classification. It is recognized that the state of knowledge concerning the application of ground support systems within a rock classification system is unsatisfactory. It appears that no serious attempt has been made to establish a universal engineering classification of rock suitably incorporating ground support and the most important geologic factors in the excavation system. This would, of course, be incomplete without discussion of the Terzaghi concept of rock loads proposed in 1946 (20). Terzaghi's theory occupies a very prominent position in American practice because of its almost universal acceptance and widespread application in perhaps hundreds of tunnels. Terzaghi offered a system of rock classification and a method of estimating rock loads imposed on supports. The reader will note that the method apparently fails to go that one small step further to make direct integration into the excavation and support system toward a final design. This oversight can be attributed to the lack of sufficient case history data. Terzaghi wrote as follows (20, pg 69):

> "Our knowledge of the intensity of rock loads on tunnel supports is derived chiefly from the results of tests which were carried out in various railroad tunnels in the eastern Alps. In these tests wooden blocks with known strength were inserted between the individual members of the timber sets and the load on the timbering estimated from the progressive failure of the blocks."

As the foremost proponent of the Case History method it is only speculation to what may have developed had Terzaghi had access to the wealth of data

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20) Terzaghi, Karl. Rock Defects and Loads on Tunnel Support. 100 pg, in Rock Tunneling with Steel Supports. The Commercial Shearing and Stamping Company, Youngstown, Ohio, 1946, 278 pg

from more recent projects. Several recent publications have reviewed the state-of-the-art in rock classification with reference to tunneling (21, 22, 23, 24).

A review of rock classification for engineering use given in this Appendix proposes the following informal rules:

1. Classification is an essential part of any subject.
2. Classification always evolves.
3. No classification can achieve perfection.
4. A sufficiently accurate classification can be developed for specific application.
5. The classification must be simple if it is expected to be widely used.
6. The classification must use terms understood by all users.
7. The classification must have regard for the material being classified.
8. A classification must be able to assist those using it.
9. A classification must consider the "most important" factors with due regard for not allowing any "inadmissible simplifications".

Although portions of this procedure may seem incomplete from the viewpoint

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21) Coates, D.F. Classification of Rock for Rock Mechanics. Int. Journal Rock Mech. and Mining Science, v. 1, No. 3, 1964, pg 421-429

22) Deere, D.U. and R.P. Miller. Engineering Classification and Index Properties for Intact Rock. AFWL-TR-65-116, Univ. of Illinois, AD 646 610, December 1966, 300 pg

23) Deere, D. U., A.H. Merritt, and R.F. Coon, Engineering Classification of In-Situ Rock. AFWL-TR-67-144, Univ. of Illinois, AD 848 798, January 1969, 272 pg

24) John, M. Properties and Classification of Rock with Reference to Tunneling. National Mech. Eng. Research Inst., Council for Scientific and Industrial Research, Pretoria, South Africa, CSIR Report MEG 1020, June 1971, 54 pg

of the theoretician, a classification system can be constructed such that it will not involve any inadmissible simplifications of the actual situation. The self-imposed goal of any ground support prediction model, therefore, is to be assured that all important factors were considered and are understood by all users and that "inadmissible simplifications" have not occurred. This research has achieved a relationahip between rock load and support requirements with a quantitative index classification of rock.

APPENDIX E

REMOTE SENSING

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Throughout this report great emphasis has been given to the pre-bid estimate of ground support requirements in the tunneling system. The approach given in this analysis has been conventional project engineering through evaluation of prior support practices projected to a common basis of rock structure rating (RSR). Further promise of the pre-excavation knowledge of rock structure has long been advocated by researchers using geophysical instruments and remote sensing. For purposes of this appendix both subjects shall simply be termed remote sensing. It is not intended to cover the entire field of remote sensing but primarily to cover those areas within the Bureau of Mines research effort under the ARPA program[1] which have bearing on ground support prediction techniques. All are contract research projects funded as one or two year efforts within the same time frame as this contract. Each project has received theoretical and laboratory investigation and at least one field demonstration. In the following project commentaries, no remarks have been made as to the success of each remote sensing technique for the simple reason that some have achieved success while others have not; whereas in future applications, under other field conditions, the reverse may occur.

Title: Electromagnetic Pulse Sounding for Geological Surveying

Contractor: The Ohio State University, Columbus, Ohio

Contract No: HO 210042 (FY 71)
HO 230009 (FY 72)

Final Report Number: AD 754847 [2]

Objective and Summary:

To develop a method of volumetric subsurface geologic mapping using electric pulse sounding techniques. Study the feasibility of determining the type, location, and size of geologic conditions and man-made objects in the area of underground excavation from the spectral content of the echo pulse.

Analytical studies were conducted to secure design data for the pulse sounding probe and to allow scattering characteristics of planar and spherical contrasts to be idealized models of geologic anomalies. Measurements were made with a 5 volt peak pulse generator (3 ns base, 2 MHz repetition rate). In addition to numerous probe tests and control target measurements, a number of targets (various sizes of metal and plastic pipes buried in overburden) were measured using the probe in the orthogonal mode.

Title: Excavation Seismology

Contractor: Honeywell Research Inc., Minneapolis, Minnesota

Contract No: HO 210025 (FY 71)
HO 220070 (FY 72)

Final Report Number: AD 742146 (FY 71)

Objective and Summary:

Evaluate the effectiveness of selected principles and techniques in determining subsurface geologic conditions. Increase the quality of geologic data obtained by seismic and/or acoustic methods in underground excavations. Establish the compatibility of the system concept with the requirements of rapid underground excavation.

The seismic reflection method was considered the most suitable application.

The principle technical problem was identification of reflections superimposed on other source-produced coherent interference. Signal processing techniques, including cross-correlation and velocity filtering (or beamforming) using an array of receiving sensors, were investigated for enhancement of reflections. A seismic source/receiver combination was developed which produces a simple, repeatable transmitted seismic pulse. A field recording system was assembled and seismic signals recorded and digitized for reflections from free surfaces on grantie, both in blocks and in situ, using a single receiver at various locations to simulate an array of receivers. The digitized signals were subsequently processed by digital computer to simulate and assess signal processing techniques. Two seismic array processing techniques were verified and evaluated. A prototype portable seismic/acoustic system was successfully demonstrated.

Title:	Prediction of Geologic and Hydrologic Conditions Ahead of Rapid Excavation Operations
Contractor:	U. S. BuMines
Contract No:	BuMines In-House FY 71 BuMines In-House FY 72
Final Report Number:	AD 748637

<u>Objective and Summary</u>:

Develop improved techniques for detecting, delineating, and evaluating geologic and hydrologic conditions, as well as man-made, in advance of rapid excavation operations to allow preventative or evasive action to be taken along the line of a tunnel.

A mobile geophysical well logging unit was designed, developed, and calibrated for use in vertical drill holes. The well logging system for making measurements of physical properties of rock penetrated by vertical drill holes was directed to special needs of geological-hydrological prediction problems associated with tunneling. Models were developed for providing a means of improved quality control required for the measurements of interest. A new interpretive technique for determining P- and S- wave velocities from acoustic logs was developed and preliminary tests were performed to evaluate its effectiveness.

Title:	Research in Long Hole Exploratory Drilling for Rapid Excavation Underground
Contractor:	Jacobs Associates, San Francisco, California
Contract No:	HO 210037 (FY 71) HO 220020 (FY 72)
Final Report Number:	AD 743224 AD 753052

Objectives and Summary:

Provide an optimum drilling system for exploration drilling in advance of underground excavation projects. This system is consistent with requirements of drill-and-blast and mechanical boring methods of driving tunnels with emphasis on the latter.

A novel horizontal rock drilling method was developed. Hardware has been produced and assembled to provide a long-horizontal probe-hole drilling machine. The drill is instrumented to record data for selecting the best combination of thrust, RPM, fluid, air flow rates and pressures. The test drill components and methods were selected with ultimate space and underground environment limitations in mind. A new method of handling 1,000 feet of drill rod in a single piece was also developed. This method provided a new concept in circulating fluid (air or water) through the storage pipe and into the open end of the drill rod stored in it. The research developed a drill to make a hole 4 inches in diamater and 1,000 feet deep. The drill is capable of coring, as required, 5 feet of solid core at least every 50 feet of advance.

Title:	Research on Tunnel Site Selection by Remote Sensing
Contractor:	University of Michigan, Willow Run Laboratory, Ann Arbor, Michigan
Contract No:	HO 210041 (FY 71) HO 220064 (FY 72)
Final Report Number:	AD 748663

Objective and Summary:

To develop an airborne remote sensing system comprised of the simultaneous application of microwave radar, multispectral scanning, radiant energy, and aerial photographic equipment for use in siting large-scale underground structures. Interpretation and analysis of this imagery shall provide as complete a description as possible of the surface geologic features in selected regions of this imagery.

An investigation was designed to utilize simultaneously aerial photographs, microwave radar, and multispectral scanners for geologic study. These were used in conjunction with ground truth investigations in an attempt to construct geologic and lithological maps applicable to the selection of tunnel sites. Vincent's image ratioing technique was used to determine different types of surface and subsurface features. Various types of coherent optical processing techniques were studied for the enhancement of geologic studies in radar imagery. The potential for using both high-resolution L band and X band and cross-polarized synthetic-aperture radar imagery was investigated.

Title:	Seismic Determination of Geologic Discontinuities Ahead of Rapid Excavation
Contractor:	Bendix Research Laboratory, Southfield, Michigan
Contract No:	HO 210033
Final Report Number:	AD 749977

<u>Objective and Summary:</u>

Evaluate the feasibility of applying ultrasonic acoustic methods to detect large geological discontinuities that might affect excavating conditions, within a reasonable working range and ahead of excavation.

The feasibility of using several non-destructive ultrasonic techniques for detecting the presence of large geological discontinuities was demonstrated. The pulse reflection method was found to be best suited to the proposed application. A study was undertaken to determine the optimum radiation frequency (or range of frequencies) most likely to delineate geological discontinuities, with a given working range, ahead of the excavation. Field tests were conducted at the Colorado School of Mines experimental mine.

Title: Seismic Holography for Underground Viewing

Contractor: Bendix Research Laboratories, Southfield, Michigan

Contract No: HO 210032 (FY 71)

Final Report Number: AD 746498

Objective and Summary:

Develop seismic holography system for underground viewing capable of detecting and locating tunnels, mines, bunkers, other anomalies, and features of the earth using principles of acoustic holography. The ability to accurately determine potential hazards and drastic changes ahead of excavation shall be investigated.

A theoretical analysis was performed to determine requirements of a holography system for processing seismic data to map tunnels, bunkers, mines, and/or various discontinuities in rock. The contractor designed a series of experiments based on on-site as well as off-site data. Computer models of the test site were developed and computer simulation studies were made to further develop a holographic weak-signal-enhancement technique (WSET). Computer programs were written to calculate the straight line ray paths for body waves.

Title: Techniques for Measurement of Ground Characteristics in Advance of Excavation in a Marine Environment

Contractor: Marine Minerals Technology Center, Tiburon, Calif.

Contract No: HO 210016 (FY 71)
HO 220019 (FY 72)

Final Report Number: AD 737282
AD 763811

Objective and Summary:

To develop techniques and to evaluate the feasibility of using geophysical instrumentation in a marine application to measure physical properties of seafloor sediments and rock in order to predict geologic conditions in advance of excavation. Design, model, and laboratory test actual systems to determine their feasibility for application to the problem.

Mass physical properties of seafloor sediments and rocks were determined using geophysical tools for the identification of associated parameters. A direct current resistivity system, fashioned after the land-oriented Wenner array, was successfully developed. A prototype seismic shear wave generator was built for marine sediments. A reflectivity experiment to classify seafloor sediments was performed.

Title: Thermal Monitoring of Geologic Changes During Excavation

Contractor: Bendix Research Laboratory, Southfield, Michigan

Contract No: HO 210031 (FY 71)

Final Report Number: AD 755117

<u>Objective and Summary</u>:

To determine the feasibility of using the local temperature distribution along the walls of an excavation to aid in predicting hazards to tunneling operations.

Information pertaining to possible temperature conditions, rock formations, and general mining environmental conditions as well as information about the state-of-the-art was obtained using noncontact temperature measuring devices. Calculations were performed on theoretical models of temperature fields around geologically different areas in an otherwise homogeneous rock matrix. Numerical data pertinent to radiometer design were obtained. Radiometer tests were conducted at the experimental mine at the Colorado School of Mines and at Republic Steel Corp. mine at Mineville, New York.

The remote sensors described in the preceding commentaries provide a wealth of valuable data for earth science research. These remote sensing methods have been shown to include ultrasonic acoustical methods, seismic holography, seismic reflection, geophysical well logging, marine geophysics (applicable to under-water tunneling) electromagnetic pulse sounding, thermal monitoring, simultaneous aerial photographs-microwave radar-

multispectral scanners, and long-hole drilling. This appendix is concerned mainly with the new and heretofore little used "unconventional" remote sensing techniques defined by the BuMines/ARPA effort. The use of remote sensing data for geology and tunnel siting is in its infancy for some techniques, such as microwave radiometry, and highly advanced for others, such as conventional aerial photography.

In the currently used photographic methods common aircraft are used in the 10 to 15 Km altitude, low-orbit manned spacecraft and the new Earth Resources Technology Satellite (ERTS-1) at higher altitudes. On July 23, 1972 the National Aeronautics and Space Administration (NASA) launched the first Earth Resources Technology Satellite (ERTS-1). This satellite is maintained in a near-polar, near-circular, sun-synchronous orbit circling the earth 14 times per day, and oriented so that each point on the earth's surface can be viewed repetitively every 18 days. Each image is 115 x 115 miles, or nearly 13,000 square miles. Through its ability to photograph large areas of the earth's surface, ERTS imagery appears ideally suited to the problem of initial tunnel route selection and comparitive geologic and topographic analysis. With relatively little effort, satellite imagery may be converted into various types of maps - planimetric, topographic, and geologic - and at reported savings over normal, ground-based mapping techniques. Further, the ability to re-map any point on the earth within 18 days would appear especially advantageous. All ERTS imagery is available for sale to the public.[3]

Properly used, to supplement other geologic and geophysical techniques, remote sensor data should be of immense value for tunnel siting, especially regional studies and in unknown areas. As with most techniques, remote sensing is neither a panacea, nor uniformily applicable or useful; judicious engineering decisions must still be made as to questions of when, how, and where to use remote sensing data. Even in reasonably well known areas, where detailed mapping is available, the proper application of remote sensing could provide information not otherwise obtainable, and could result in a better understanding of tunnel siting in a shorter time.

Throughout this appendix it is obvious that considerable field and design experience is required to develop proper engineering criteria and adequate design expertise for purposes of pre-bid ground support prediction. Two different directions are required: (1) Improvement of remote sensing instrumentation and (2) Improvement of interpretation in the remote sensing measurements in relation to the field geology. The interpretation of remote sensing data is a distinct disadvantage at this time - simply due to the human element of "interpretation" which requires needed field experience by well qualified personnel. Secondly, even though vastly improved remote sensing instrumentation has been recently developed, the depth of investigation is insufficient for purposes of tunnel siting at great depth (as in the classic example of the Roberts tunnel in Colorado [4]). Therefore, regretably, most of the known geophysical and remote sensing methods and techniques are not suitable for subsurface tunneling conditions beyond a few hundred

feet of depth, either ahead or below the point of investigation.

It should be fully appreciated that the results of geophysical explorations are interpretations of physical measurements and are not, in themselves, geologic facts relative to the subsurface at a test locality.

The common surface drilled bore-hole method of exploration remains the most viable method of obtaining necessary pre-bid data for the RSR method of ground support prediction. The drill core provides direct rock samples for laboratory testing as well as providing a means for making a variety of subsurface down-the-hole geophysical measurements. As such, bore-hole exploratory methods probably rank as the best universal exploration tool yet available.

As noted in the remote sensing commentaries, two BurMines/ARPA research projects have fulfilled this need. An in-house BurMines research project was responsible for developing a well-logging system for making measurements of physical properties in small diameter vertical drill holes to satisfy the special needs of geologic-hydrologic investigations in tunnel siting. This well logging system has been successfully demonstrated. The second project (HO 210037 and HO 220020) was an ARPA contract project to develop the necessary equipment and techniques for exploratory drilling from the tunnel face of either conventional drill-and-blast or machine bored openings horizontally ahead for at least 1,000 feet. The drilling system successfully field demonstrated the drilling of a 4 inch diameter hole and the capability of taking cores as needed.

Finally, a bibliography Abstract search, as required for all contracts, was requested from the National Technology Information Service (NTIS) for remote sensing reports between 1962 and 1972. Over 400 reports were contained in the search document, and although a reading of all Abstracts revealed application of remote sensing to nearly every subject field there were no investigations directly related to tunnel siting except the BuMines/ARPA projects.

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1 Further information on remote sensing projects under the BuMines/ARPA program may be obtained from Mr. James J. Olson, Twin Cities Mining Research Center, Twin Cities, Minnesota 55111.

2 All reports may be ordered from National Technical Information Service (NTIS), U.S. Dept. of Commerce, Springfield, Virginia 22151

3 EROS Data Center, U.S. Geological Survey, Sioux Falls, South Dakota 57198

4 Wahlstrom, E.E. The Validity of Geologic Projection, A Case History. Econ. Geol., v. 59, No. 3, 1964, pg 465-474.